CANOPY TEMPERATURE AND
CROP WATER STRESS

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I. Introduction

Production of agricultural crops in the arid areas of the world is almost totally dependent on irrigation. In semiarid areas, irrigation is increasingly used to supplement rainfall. In normally humid areas, irrigation systems are being installed to offset the yield-reducing stress conditions that ensue after a few weeks without rain. Although the number of irrigation systems is growing, the supply of water available for irrigation is decreasing. This, coupled with the steeply rising costs of the energy required to pump and move water to the desired location, is causing an increased emphasis to be placed on means of attaining the maximum benefit from each unit quantity of water used for irrigation.

One aspect of irrigation science that has been of interest for some time is irrigation scheduling. Even today, many farmers irrigate by the calendar, while others receive water at scheduled times and therefore use the water whether their

crops need it or not. Another group, composed largely of farmers in high-energy-use areas who can control their water deliveries, is searching for ways to determine the most beneficial time to apply just the right amount of water.

In general, irrigation-scheduling techniques fall into three categories: soil based, meterologically based, and plant based. Combinations of the three categories are sometimes used. An example of a soil-based technique is the monitoring of soil water content within a field. Knowing the "field capacity" and the "wilting point" of the field soil, soil water content information allows estimation of the amount of water lost in evapotranspiration and drainage below the root zone. When the soil water content falls to certain value, the amount required to bring the soil profile back to field capacity is to be added by irrigation. Although in some places soil water content is still measured by the time-honored method of determining the weight of water in a sample, the neutron moisture meter (Van Bavel et al., 1963; Bell, 1976; Nakayama and Reginato, 1982), has become commonplace. This method has been tried for a large portion of an irrigation district in western Arizona (Gear et al., 1977). The technique assumes uniform soil properties throughout the field, since only one or two point measurements are made in each field. Furthermore, the only plant response parameter used in the technique is an indirect one through the wilting-point estimation.

Meteorological methods have been developed by a number of researchers (Jensen and Haise, 1963; Heermann et al., 1976; Jensen and Wright, 1978; Wright and Jensen, 1978). Basically, these methods use air temperature, net radiation, vapor pressure, and wind speed as inputs to models which calculate the amount of water evapotranspired during a given time period. When the evapotranspiration reaches a certain value, irrigations are deemed necessary. The meteorological methods do not directly account for drainage below the root zone, and no direct plant information other than crop coefficients are used. These methods have been used with programmable calculators (Kincaid and Heermann, 1974; Kanemasu et al., 1978).

Direct measurement of some plant parameter would appear to be a superior method for timing of irrigations in that the plant responds to both its aerial and soil environments. Such methods are generally limited to measurements on individual plant parts such as leaves and petioles. Examples are the pressure bomb (Scholander et al., 1965), the leaf diffusion porometer (Kanemasu, 1975), and petiole and leaf water content measurements (Longenecker and Lyerly, 1969). These methods are time consuming and require numerous measurements in order to characterize a field.

Hiler and Clark (1971) and Hiler et al. (1974) developed a *stress day index* (SDI) based on plant parameters. The SDI was the product of a plant stress factor and a crop susceptibility factor. The former is an indicator of the crop's water deficiency and the latter is a function of the crop species and stage of growth.

After testing several plant measurements (including leaf temperatures), they selected the plant water potential as a stress indicator. Their concepts of stress quantification were expanded by Stegman *et al.* (1976), who related the xylem pressure of leaves to the ambient air temperature and the available soil moisture. Their results indicated a substantial decrease in the amount of water used without a reduction in yield for crops irrigated using scheduling techniques based on plant stress indicators.

Although leaf temperature did not prove sufficiently sensitive for Hiler *et al.* (1974) to use in their SDI, Ehrler (1973) found it to be a good indicator of stress, if vapor pressure effects were accounted for. He suggested that leaf temperature could be used for irrigation scheduling. Hsiao (1973), in a detailed review of plant water stress, stated that "... it would be reasonable to assume that elevation in leaf temperature does not play a general role in water stress effects." With such differing views on the usefulness of leaf temperatures for evaluating crop water stress, the issue is, to say the least, confusing.

Even if leaf temperature is, in principle, a good indicator of plant water stress, measurements on individual leaves suffer the same disadvantage as other point measurements, namely that many samples must be taken to adequately characterize a field. Recent advances in IR thermometry obviate that disadvantage by offering the possibility of rapidly surveying a large number of plants and integrating plant temperatures over entire fields or characteristic sections of fields.

This article progresses from the voluminous literature on leaf temperatures to the use of IR thermometry to determine canopy temperatures, and on to energy balance considerations. It develops a basis for the evaluation of plant stress from canopy temperature, vapor pressure, and net radiation data. A *crop water stress index,* as derived from theoretical considerations and empirical data, is discussed in detail. This index, similar in many respects to the SDI of Hiler *et al.* (1974), can be rapidly obtained by surveying a field with an IR thermometer, measuring wet- and dry-bulb air temperatures, and estimating net radiation. Its potential for use in the timing of irrigations appears promising.

II. Historical Perspective

The use of canopy temperatures to detect water stress in plants is based upon the assumption that transpired water evaporates and cools the leaves below the temperature of the surrounding air. As water becomes limiting, transpiration is reduced and the leaf temperature increases. If little water is transpired, leaves will warm above air temperature because of absorbed radiation.

There are reports in the literature that argue strongly that leaf temperatures are always warmer than the surrounding air. Others argue just as strongly that leaves can become much cooler than the air. The first argument has prevailed for years,

and the numerous reports expounding that view are often cited as evidence that a measurement of leaf temperature is not a sensitive water stress indicator. These diametrically opposite points of view can perhaps be reconciled by examining them from an historical perspective. We shall therefore proceed to review the pertinent literature in chronological order. This review is not intended, however, to be exhaustive. For an annotated bibliography concerning applications of remote sensing for assessing crop water deficits, see David (1969). Hsiao (1973) compiled an excellent review of water stress in plants, and Cihlar (1976) prepared a bibliography on thermal IR remote sensing.

A. LEAF TEMPERATURES

The literature concerning leaf temperatures dates back at least to the early part of the last century. Ehlers (1915) cited a paper by Rameaux (1843) who reported placing a number of leaves still attached to their stems on top of one another and wrapping the stack around a mercury thermometer. Askenasy (1875), as cited by Ehlers (1915) and by Ansari and Loomis (1959), measured the temperature of leaves of succulent plants by placing a mercury thermometer on the upper surface of a leaf and by inserting it in a cut made for that purpose. He observed that thin leaves in sunshine were 4–5°C warmer than air, and that thick leaves were in excess of 20°C over air temperature. Askenasy recognized the effects of reradiation, air movement, and transpiration on the cooling of leaves.

Ehlers (1915) was concerned with determining how evergreen leaves accumulated food in winter, his thesis being that the leaves were warmer than the air and could therefore photosynthesize at rates higher than would be calculated using air temperatures. His results (obtained in Michigan) showed that leaves of evergreen conifers were 2–10°C above air temperature.

Miller and Saunders (1923) measured the temperature of leaves of crop plants under natural field conditions in Kansas. They used a clamp made from brass tongs modified by enclosing the ends with cork. Thermocouples were embedded in the cork in such a manner that they would contact the leaf surface when the clamp was closed. About 15 sec were required to obtain a measurement. They concluded that turgid leaves of most crops were essentially at air temperature, but alfalfa consistently showed a temperature of about 1°C below the temperature of the air. These results were perhaps the first to show that leaf temperatures may be less than air temperatures under field conditions. They were later criticized by Clum (1926) and by Curtis (1936), who claimed that the leaf temperature was changed by the clamp shading the leaf.

Clum (1926) attempted to correlate leaf temperatures and transpiration. He measured leaf temperatures by threading fine thermocouples through the mesophyll. Air temperatures were measured by a thermocouple junction hanging freely in the air, usually in the shadow of one of the leaves containing one of the

other junctions. Measurements were made on potted plants both in the greenhouse and in full sunshine. Some pots were watered more than others to achieve different transpiration rates. He found that the leaves were always warmer than the air by 5-10°C. In no case did he find a definite correlation between the transpiration rate and the leaf–air temperature difference. (Clum's paper is noteworthy for its excellent literature review.)

Eaton and Belden (1929) measured cotton leaves in Arizona and found leaf temperatures to be 2-4°C below that of the air. Curtis (1936) explained their results on the basis that the low humidity allowed long-wave energy to radiate to the clear, cold sky, thus cooling the leaves. Watson (1934) reported that radiative cooling and transpiration were equally important in controlling plant temperatures. Curtis discounted the effect of transpiration in cooling the leaves. His own experiments showed that leaf temperatures may be changed several degrees by allowing or preventing radiation to cold objects or to space. He also questioned data taken by other investigators that reported leaf temperatures to be less than the temperatures of the air on the basis that their readings for the latter were probably too high.

Wallace and Clum (1938) continuously recorded leaf and air temperatures of garden plants. They found leaf temperatures as much as 7°C below air temperature (as measured by a thermocouple suspended in the air directly behind and in the shade of the leaf). They showed that leaf orientation plays a major role in the temperature regime in that leaves were generally warmer than the air when facing the sun but cooler when at oblique angles. They concluded that the loss of energy to the sky did not explain the fact that the leaves were often below air temperature.

The ink was hardly dry on Wallace and Clum's paper when Curtis (1938) offered a strong rebuttal to their conclusions. He maintained that the air temperature, as measured by Wallace and Clum, was probably 2-7°C above true air temperature, at least part of the time. He concluded by stating that impossibly high transpiration rates would be required to lower the temperature of a leaf below that of air when in direct sunlight.

Waggoner and Shaw (1952) measured the temperature of potato and tomato leaves in Iowa. They found that on clear days, upper exposed leaves were 3.3-8°C warmer than the air temperature in an instrument shelter. Lower leaves were 0.5-0.8°C cooler than the air. They found no difference between similarly exposed potato and tomato leaves.

Ansari and Loomis (1959) measured leaf temperatures on a number of plants in a greenhouse, in the open, and in a dimly lit laboratory. The only leaves that they found to be below air temperature were cotton leaves in very dim light and 25% relative humidity. They concluded that leaves are warmed by air temperatures and radiation and cooled primarily by conduction to the air.

A theoretical heat transfer analysis by Wolpert (1962) showed that the temper-

ature of a typical plant leaf was dominated by convection, assuming that the leaf remained motionless. If the leaf flaps due to wind, water evaporation controls leaf temperature. Gates (1964a) calculated the energy balance for a single leaf and concluded that transpiration was very important in the energy budget of plants. His calculations indicated that sunlit leaves would be warmer than air and the lower shaded leaves would be cooler than air.

Wiegand and Namken (1966) measured air temperatures at plant height with shielded thermocouples, and cotton-leaf temperatures with an IR thermometer. They observed that 30-45 sec were required to regain equilibrium temperature when insolation changes caused by clouds occurred. They showed that leaf temperatures increased linearly with increasing insolation, and decreased linearly with increasing relative turgidity of the leaves. The leaf-air temperature difference increased with increasing insolation (from $-3.5°$ to $+6°C$ for the "wet" treatment), but was different for each irrigation treatment. They concluded that leaf temperature interpretation requires simultaneously measured radiation data, and that the early afternoon is a good time of day for making leaf temperature measurements.

Stevenson and Shaw (1971) showed that upright leaves were cooler than horizontal leaves of soybean. For both orientations, leaf temperatures reached $4°C$ below air temperature. Carlson et al. (1972) found that leaf temperatures increased with decreasing values of the relative leaf water content and vapor pressure deficit. They observed that leaf temperatures of two soybean varieties were significantly different.

Clark and Hiler (1973) compared leaf water potential, leaf diffusion resistance, and leaf-air temperature differences (leaf temperatures measured with IR thermometers), of well-watered and water-stressed peas. Their air temperature reference was 1 m above the canopy. The data showed that leaves of well-watered peas were almost always cooler than the air and that leaves of plants on the stressed plot were $2-3°C$ warmer than leaves of well-watered plants. They concluded that leaf water potential was more responsive to changes in plant water status than either leaf diffusion resistance or the leaf-air temperature difference. These results were used by Hiler et al. (1974) in refining the SDI.

Ehrler (1973) directly addressed the possibility of using leaf-air temperature differences as a guide to irrigation scheduling. In field experiments with cotton he placed fine wire thermocouples in leaves and measured the air temperature and the vapor pressure at 1 m above the crop. His results showed a leaf-air temperature difference that ranged from $-3°$ to $+2°C$, depending on the degree of soil water depletion. A significant result of this study was the demonstration of a linear relation between the leaf-air temperature difference and the vapor pressure deficit. This relation is shown in Fig. 1. The leaf-air temperature difference decreased about $1.3°C$ for each kPa increase in vapor pressure deficit. Ehrler's data indicated that the use of leaf temperatures for irrigation scheduling was
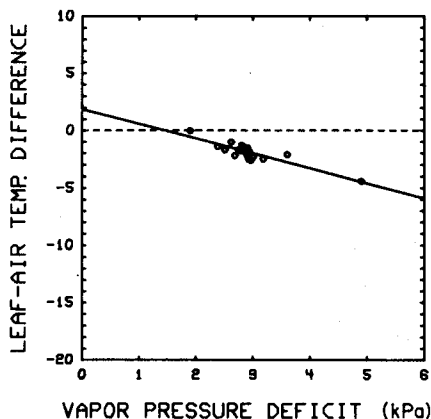
FIG. 1.   The leaf–air temperature difference versus vapor pressure deficit for four varieties of cotton. Data were taken on predominantly sunny days when the crop was fully hydrated. Data points represent the mean of three replications (after Ehrler, 1973): slope, -1.29; intercept, 1.87; $R = 0.87$.

feasible. However, the measurement of individual leaf temperatures with thermocouples was cumbersome and tedious. Many leaves must be sampled in order to obtain a reasonable average for an entire field.

Sandhu and Horton (1978) found leaf temperatures of water-stressed oats to be 2.5–4.0°C warmer than well-watered oats. They attributed the temperature differences primarily to differences in transpiration. Sumayao et $al.$ (1980) found that leaves of corn and sorghum, when well watered, were warmer than air when the air temperature was less than 33°C and cooler than air when the air temperature was greater than 33°C. Their results supported those of Linacre (1964, 1967) who first proposed 33°C as the "crossover" temperature. This constant value was disputed by Blad and Rosenberg (1976) who found that the crossover point for alfalfa occurred at temperatures between 23° and 30°C. Idso et $al.$ (1981a) argued that a constant crossover temperature does not exist, but rather that it is dynamic and dependent on the vapor pressure deficit.

With the exception of Idso et $al.$ (1981a), the papers reviewed in this section have been concerned with individual leaves. It is not surprising that the majority of the authors reported data that showed leaf temperatures greater than the air temperature. Many leaves were near the top of the plant and in direct sunlight. Air temperatures were measured in a variety of locations, ranging from the shade of the leaf to a meter or so above the plant, with no standard location suggested. Results were reported for single potted plants standing alone, without the canopy effects created by surrounding plants.

A number of experiments were conducted in glasshouses where the humidity was high. A majority of the field investigations were conducted in humid areas.

It will be shown in a later section that, theoretically, under conditions of high humidity, leaf temperatures will equal or exceed the air temperature. Field experiments conducted in semiarid areas, on the other hand, showed leaf temperatures to be as much as 7°C below that of the air.

Reradiation, convection, and transpiration were cited as the major means of cooling leaves exposed to radiation. For single leaves, transpiration was seldom indicated as a major cause of cooling. In fact, several studies discounted transpiration as an important cooling mechanism.

Part of the confusion about the use of leaf temperatures as plant water stress indicators arises, therefore, from the numerous studies on the temperature of single leaves on single plants; whereas in irrigation management, entire plant canopies are of concern. Gates (1964a) examined differences between single leaves and entire canopies. He measured Bowen's ratio (the ratio of sensible to latent heat exchange) for single leaves at several times during the morning hours. He found that the ratio increased throughout this period. This indicated that a single leaf exposed to sunlight would lose proportionally more heat by convection than by transpirational cooling as the temperature increases. However, lower leaves would have smaller values of the ratio, with the canopy as a whole having quite small values. These results were supported by the detailed calculations of Idso and Baker (1967). They concluded that for individual leaves reradiation was the major mode of heat transfer, but for canopies as a whole transpiration was the dominant mechanism. One can conclude that for a canopy (versus an individual leaf), transpirational cooling plays a major role in the energy balance, and therefore in determining plant temperature. Conversely, plant canopy temperature should be related to transpiration, and hence might serve as an indicator of plant water stress.

A problem encountered with leaf temperature measurements of field plants is that of variability. In water-stressed plots, leaf temperatures of plants 2 m apart were found to differ by 5.9°C, in contrast to relatively uniform temperatures for neighboring plants in well-watered plots (Blad et al., 1982).

During the past 20 years, IR technology has developed to the point that canopy temperatures (both sunlit and shaded leaves, stems, and other plant parts) can readily be measured. With this development, the potential usefulness of plant temperature measurements to quantify plant water stress has greatly increased.

B. CANOPY TEMPERATURES

The extension of temperature measurements from individual leaves to canopies became possible with the development of instruments that measure emitted thermal radiation. Such instruments can be calibrated to read directly in terms of temperatures. Monteith and Szeicz (1962) and Tanner (1963) were among the first researchers to use IR radiometers to measure plant temperatures. Monteith and Szeicz (1962) presented a theoretical discussion concerning the

relation between surface temperatures and stomatal resistance. From energy balance considerations, they derived an expression relating the canopy-air temperature difference to net radiation, wind speed, vapor pressure gradient, and the aerodynamic and canopy resistances. Their work formed the basis for the theoretical development of a crop water stress index that will be discussed in Section III. Their examples illustrated the dependence of surface temperature on stomatal resistance. They suggested that radiometrically determined surface temperatures could be used to evaluate the effective stomatal resistance of field crops.

Tanner (1963) used IR thermometry to explore the possibility of using plant temperature measurements to detect moisture stress differences between plants under different water regimes. Tanner recognized that the temperature sample would be weighted toward the upper part of the plant, but pointed out that it is these portions that participate most actively in transpiration, heat exchange, and assimilation. He concluded by stating ". . . plant temperatures may be a valuable qualitative index to differences in plant water regimes. Coupled with a better understanding of transfer processes at the plant surfaces, they may serve to provide quantitative data on plant-water status."

The instruments used by Monteith and Szeicz (1962) and by Tanner (1963) were essentially adaptations of laboratory apparatus. Shortly thereafter some aircraft-mounted IR scanning radiometers developed for military purposes were declassified and became available for civilian use. It would be nearly a decade before a truly portable IR radiometer was devised for field use. During the past few years, however, IR technology has developed rapidly, and IR thermometry is now used for many purposes. To provide a background for sections on airborne and ground-based thermal IR experiments, a brief review of some principles of IR thermometry is warranted.

1. *IR Radiation Thermometry*

Infrared thermometry is a noncontact method for estimating the surface temperature of a target. In principle, the measurement does not interfere with the surface and yields a temperature that is an integrated value over the field of view of the sensor. The instrument measures the radiation emitted from the target, and relates this radiation R to the surface temperature T_s by the Stefan–Boltzmann blackbody law,

$$R = \epsilon \sigma T_s^4 \qquad (1)$$

where ϵ is the emissivity of the surface and σ is the Stefan–Boltzmann constant $(5.674 \times 10^{-8} \ \text{W m}^{-2} \ \text{K}^{-4})$, with R in units of W m^{-2}. For discussions of basic principles of IR radiation thermomety, see Fuchs and Tanner (1966), Lorenz (1968), Gates (1968), and Perrier (1971).

Most IR thermometers have filters that allow only energy within the $8-14\mu m$

wave band to reach the sensor. This wave band includes the peak of blackbody emission at normal temperatures and has relatively low absorption by water vapor. The emissivity of natural surfaces within this wave band is usually high. However, water vapor absorption cannot always be neglected, and for precise measurements the emissivity must be known. Another complicating factor is that part of the radiation emitted by the surroundings and reflected by the surface in this wave band also may strike the sensor, adding to the radiation received from the target.

a. Atmospheric Water Vapor. Lorenz (1968) stated that the influence of water vapor (in the 8–14-μm wave band) on surface temperature measurements was neglible if the distance to the target was less than 154 m. His results suggest that ground-based thermometric measurements will generally not need to be corrected for water vapor absorption, but that aircraft- and spacecraft-based measurement will need correcting. Lorenz (1968) and Heilman *et al.* (1976) show how this correction can be made, if the water vapor distribution in the atmosphere is known. Computer models such as that of Selby *et al.* (1978) are frequently used to make this correction.

b. Emissivity and Sky Radiant Emittance. Fuchs and Tanner (1966) showed that the effects of radiation emitted by the surroundings and then reflected from the target to the sensor (termed sky radiant emittance by Conaway and Van Bavel, (1967a,b) can be accounted for if the emissivity is a constant over all wavelengths within the wave-band interval, and if the filter function of the instrument is known. The flux of radiation reaching the sensor is

$$R = \epsilon\sigma T^4 + (1 - \epsilon)B \qquad (2)$$

Where B is the reflected radiation from the surroundings. Fuchs and Tanner (1966), Conaway and Van Bavel (1967a,b), and Idso and Jackson (1968) have described how B could be evaluated. If $\epsilon = 1$, then B has no effect on R. If $\epsilon < 1$ and B is neglected [as in Eq. (1)], then T_s will be overestimated. If ϵ is erroneously assumed to be 1 when it is less than 1, then T_s will be underestimated. Perrier (1971) showed that the error involved by assuming $\epsilon = 1$ is

$$(T_s - T)/T = 1 - [\epsilon + (1 - \epsilon)B/\sigma T^4]^{1/4} \qquad (3)$$

where T is the calculated apparent temperature obtained by assuming $\epsilon = 1$ and using the relation $R = \sigma T^4$. If $B = R$ then $T = T_s$, regardless of the value of ϵ. The value of B is generally less than R, and varies with sky conditions. As B decreases the error increases. The maximum error $(1 - \epsilon^{1/4})$ occurs when $B = 0$ (i.e., the true surface temperature is always underestimated). The maximum difference between the true surface temperature T_s and the apparent temperature T is

$$T_s - T = T(1 - \epsilon^{1/4}) \qquad (4)$$

Figure 2 shows the maximum $T_s - T$ versus emissivity over the range from 0.9 to 1.0. Calculations were made for two temperatures.

There are two reasons why the values shown in Fig. 2 are the maximum to be expected. The first is that the sky radiant emittance B adds to the target radiance R, causing a higher apparent target temperature. Since B, although variable, is never 0, the actual $T_s - T$ difference will always be less than that shown in Fig. 2. The second reason involves the limited bandwidth of the sensor. Sutherland *et al.* (1979) calculated the detector response for an infinite bandpass using the Stefan–Boltzmann law [Eq. (1)], and the response for an infinitesimal bandwidth using the Planck equation. They showed, with the two extremes, that the apparent temperature is not well defined but that the error is less for the infinitesimal bandwidth. Since most IR thermometers do not exceed an 8–14-μm bandwidth, the apparent temperature is generally closer to the true temperature than the lines in Fig. 2 suggest.

c. Leaf and Canopy Emissivities. The thermal IR emittance of most plant surfaces ranges between 0.95 and 1.00. Gates (1964b) stated that all plant surfaces have a long-wave emittance of 0.95 or more, with most plant leaves being 0.97–0.98. This was substantiated by Idso *et al.* (1969) who found only two of 34 plant species studied that had single-leaf emissivities less than 0.95. The emittance of a canopy should be greater than for individual leaves because of cavities formed by canopy architecture. Fuchs and Tanner (1966) and Blad and Rosenberg (1976) measured canopy emissivities and reported values of 0.976, 0.976, and 0.971. Even with soil exposed between rows of trees, the composite emittance remains high (Sutherland and Bartholic, 1977). Assuming that the
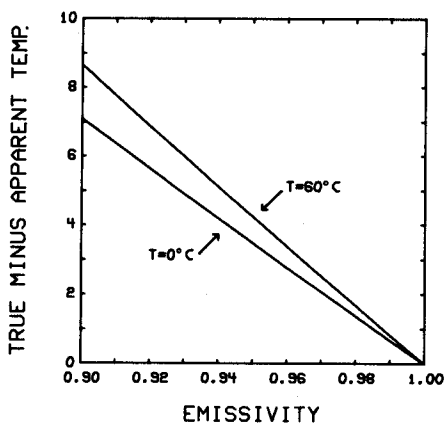

Fɪɢ. 2. The maximum increment to be added to the apparent temperature T obtained by assuming a unit emissivity, to obtain the actual surface temperature T_s as a function of emissivity for two values of the apparent temperature.

canopy emittance is on the low side, say 0.97, Fig. 2 shows that for an apparent temperature of about 30°C, the maximum error involved by assuming $\epsilon = 1$ would be about 2°C. Considering the various factors involved, it is doubtful that the error caused by assuming $\epsilon = 1$ for plant canopies would generally exceed 1°C.

d. Portable IR Thermometers.   During the 1960s IR technology advanced rapidly, and instruments that could be used in the field became commercially available. The instruments used by Fuchs and Tanner (1966) and by Conaway and Van Bavel (1967a,b) consisted of an electronic console to which a relatively lightweight sensing head was connected by a cable. The instruments required external power sources. The sensing head contained a temperature-controlled blackbody to which, during operation, the sensor was exposed alternately with radiation coming from the target. The reference blackbody temperature was above 40°C. However, during the summer months in the Southwest, when the ambient air temperature was high and the sensing head was exposed to solar radiation, the reference temperature exceeded the preset control temperature, causing erroneous readings. Ambient temperature effects on these instruments were documented by Idso and Jackson (1968), and by Jackson and Idso (1969). Subsequent designs included a battery-operated console, making the instrument portable.

Gates (1968) described a small, lighweight IR thermometer specifically designed for hand-held use. The portability of the instrument was superb. However, it required frequent calibration and was sensitive to ambient temperature changes (McGinnies and Aronson, 1971).

During the past decade a number of lightweight, hand-held, battery operated IR thermometers have become available. For the most part, these instruments were designed for use in buildings or other enclosed areas where only small temperature changes would occur. When used in the field under conditions of changing insolation and air temperature, the instruments failed because components would be changing temperature, and erroneous readings of the target temperature would result. Because of the market for IR thermometers in agricultural research and the potential market as an operational irrigation scheduling tool, several companies have addressed this problem and have made significant progress toward its solution. It is highly recommended that a potential purchaser determine whether an adequate ambient temperature compensation circuit is an integral part of any instrument that is intended for field use.

Calibration and frequent checks of calibration are essential if reliable data are to be obtained from an IR thermometer. Jackson *et al.* (1980) discussed field-use calibration and the precautions to be observed when using these instruments. Sun azimuth angles and row direction can cause a small difference in canopy temperatures (Fuchs *et al.*, 1967). Clawson and Blad (1982) found negligible directional

effects during measurements of corn canopy temperatures. Gardner *et al.* (1981b) reported a slight tendency for a southerly exposure to be warmer than plots with a northerly exposure. The effect can be minimized by taking readings from two directions 180° apart and averaging them.

2. *Airborne Thermal Scanner Experiments*

In a forward-looking science fiction type of scenario, Park *et al.* (1968) predicted the use of thermal IR imagery obtained from orbiting satellites for irrigation scheduling. Their scenario had an agronomist and a forester managing 800,000 acres of land devoted to intensive agriculture and forestry production. The two met frequently to review satellite data. Thermal imagery played a major role in their assessment of irrigated acreage. The fictional duo found "hotspots" in soybeans, but concluded that overall, their irrigation schedule had been correct. The projections of Park *et al.* (1968) were based on a few thermal images obtained from airborne scanners. The promise of remote sensing as a tool for resource management as outlined by Park *et al.* has not as yet been fulfilled. In the 13 years since they made their predictions, much has been accomplished yet much remains to be done.

Some of the data on which Park *et al.* (1968) based their predictions were reported by Wiegand *et al.* (1968). Their experiments included extensive ground measurements along with imagery from an airborne scanner. They showed that freshly irrigated crops were up to 20°C cooler than nonirrigated portions of the same fields. Myers and Allen (1968) presented similar data and stated that remotely sensed plant canopy temperatures appear to be a feasible means for assessing irrigation needs, as well as the extent and severity of drought. Later, Myers and Heilman (1969) demonstrated the effect of plant cover on remotely sensed temperatures. They showed that soil background greatly influences thermal images obtained from aircraft. .

Bartholic *et al.* (1972) were among the first to use an airborne thermal scanner specifically to determine the temperature of soils and of crop canopies differing in water stress. They observed up to 6°C differences between least- and most-stressed plots planted to cotton. From airborne data taken over Kansas, Heilman *et al.* (1976) observed that soybean was 2.6°C cooler than sorghum. Blad and Rosenberg (1976) used an airborne scanner to compare surface temperatures of wheat, alfalfa, and pasture. The wheat and alfalfa were cooler than pasture. They also used portable radiation thermometers to measure surface temperatures. Alfalfa was found to be 5–7°C cooler than air (measured at 2 m) during mid- and late afternoon. Irrigated corn, on the other hand, was always warmer than alfalfa and was usually warmer than air (except for short periods in the late afternoon). This work pointed out the necessity of studying the temperature relations of all crops of interest, since not all are alike.

Millard *et al.* (1978) presented thermal imagery for six differently irrigated

wheat plots. The stressed plot was 8°C above the air temperature measured at 1.5 m, whereas the well-watered plots were as much as 6°C below air temperature. The pseudocolored thermal imagery clearly showed the temperature differences and the temperature variations within plots. Their data showed that when full ground cover is achieved, airborne thermal imagery can readily distinguish different irrigation treatments, and that it could therefore be used as an irrigation-scheduling tool.

The soil background exposed by incomplete canopies poses a difficult problem for determining plant canopy temperatures from aircraft and spacecraft (David, 1969). A remote sensor above an incomplete canopy would see sunlit and shaded soil, and sunlit and shaded vegetation. These four surfaces would probably have somewhat different temperatures, and a composite of the various temperatures would be detected by the sensor. The problem is more serious for crops with wide rows than for crops that are broadcast or that are planted or drilled in narrow rows. Hatfield (1979) measured vertical and angular temperatures of wheat drilled in 0.18-m rows, using a 20°-field-of-view portable radiation thermometer. The angular–vertical temperature difference was near zero for low and full cover conditions, and reached a minimum of -2°C at about 40% plant cover. Heilman et al. (1981) measured temperatures from vertical and angular positions over barley. They found that the composite (vertical) temperatures were from 0.5° to 11.5°C higher than the canopy (angular) temperatures. The prediction of canopy temperatures from composite temperatures was improved by accounting for emissivity and sky radiance.

Jackson et al. (1979) modeled this problem for row crops. They assumed that plant rows could be represented by a rectangular block of specified height and width. The fractions of sunlit and shaded soils and vegetation could be calculated from sun elevation and azimuth angles for a particular location, hour, and date. Using ground-measured soil and plant temperatures for a cotton crop with 1-m row spacing, they calculated the composite temperature that a thermal scanner would see as a function of view angle. Results of these calculations are shown in Fig. 3. The maximum temperature occurred near the center of the scan because of the hot sunlit soil. As the scan moves to either side of nadir (0°), the temperature decreases. This occurs because as the scan angle increases, the amount of vegetation in the field of view of the instrument increases, and the amount of soil decreases. The scan line in Fig. 3 is not symmetrical because in one direction predominantly sunlit surfaces are seen, whereas in the other direction shaded surfaces form a significant portion of the scene. Jackson et al. (1979) suggested that concurrent measurement of reflected solar data may help in the extraction of plant temperatures from the composite scene. The problem is serious and far from solved (Gardner et al., 1981c). Since the ultimate use of canopy temperature techniques for agricultural management decisions such as irrigation schedul-
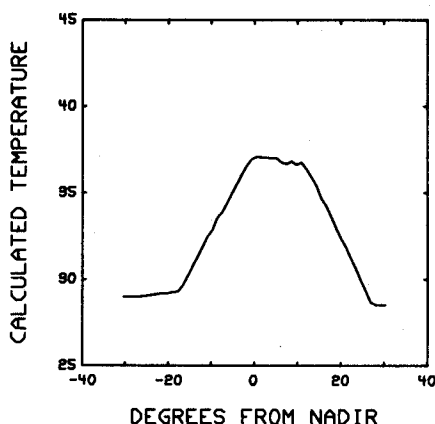
FIG. 3.   Calculated composite temperatures of row cotton as a function of view angle at 1330 hr on Julian day 196 (for east–west rows). The temperatures used in the computation were sunlit soil, 55.3°C; shaded soil, 31.1°C; sunlit vegetation, 28.5°C; shaded vegetation, 29.5°C (from Jackson *et al.*, 1979).

ing will probably be from aircraft or spacecraft platforms, a solution to this problem is urgently needed.

3. *Ground-Based Canopy Temperature Experiments*

Aston and Van Bavel (1972) proposed that soil water depletion could be remotely detected by determining the increase in visible and thermal radiant heat loads upon plant leaves as the underlying soil surface dries. They cautioned that the temperature differences involved would be both small and variable. As plant cover increased the differences would become smaller. For full canopies, however, another approach could be taken. Aston and Van Bavel suggested that because of the inherent heterogeneity of soils, various locations in a field would become stressed before others, and the canopy temperature would show a greater variability than under well-watered conditions. They proposed that the variability of temperatures within a field be used to signal the onset of water deficits.

Stone and Horton (1974) installed an IR radiometer above a field of grain sorghum. They used the radiometrically measured canopy temperature along with the air temperature to calculate evapotranspiration (ET) using equations developed by Bartholic *et al.* (1970) and by Brown and Rosenberg (1973). One objective was to show that remotely sensed surface temperatures could be used to obtain regional ET estimates. Blad and Rosenberg (1976) mounted an IR radiometer over a crop of alfalfa and compared the resulting temperatures with leaf thermocouples and with aircraft scanner-derived temperatures. They made

qualitative comparisons between ET of corn and alfalfa based on temperature measurements.

  a. Stress Indices. Idso *et al.* (1977) and Jackson *et al.* (1977) measured canopy temperatures every day throughout a complete wheat-growing season. Their purpose was to develop techniques for evaluating crop water stress remotely with a minimum of measurements. They assumed that environmental factors (such as vapor pressure, net radiation, and wind) would be largely manifested in the canopy temperature, and they defined a *stress degree day* (SDD) as the difference between the canopy temperature T_c and the air temperature T_A. They reasoned that the SDD would increase with increasing plant water stress. Idso *et al.* (1977) used the SDD to predict final yields. They plotted the cumula-
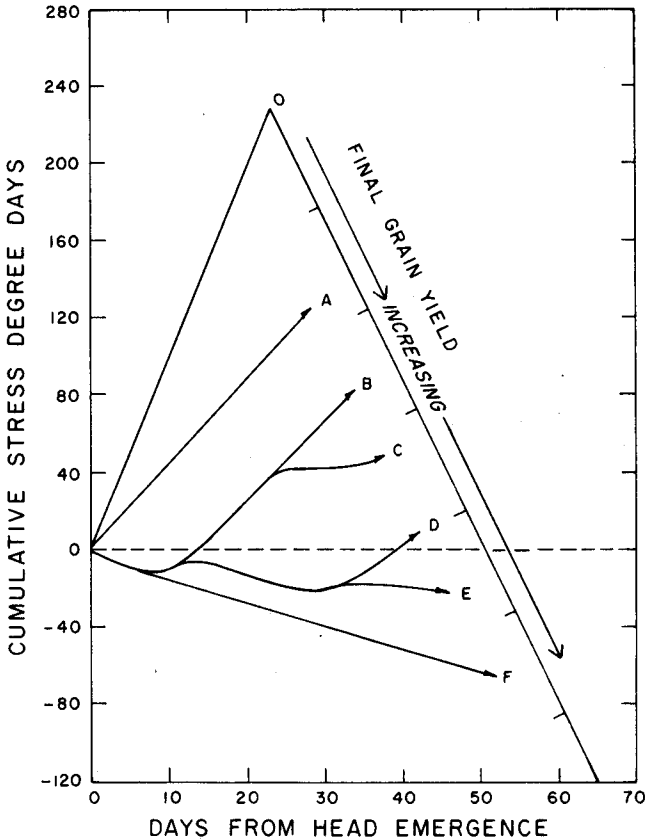

Fig. 4. Cumulative SDDs from the time of head emergence for Produra wheat. The lines A–F represent typical paths by which six differently irrigated plots approached final yield (after Idso *et al.*, 1977).

tive SDD from heading to maturity as a function of time for several wheat plots
that had received different amounts of irrigation water. Figure 4 is a generalized
plot of their results. Lines A–F indicate time courses for the different water
treatments. All plots were irrigated immediately after planting. Line A resulted
when no additional irrigations were given. The cumulated SDD increased con-
tinuously with time, and a low final grain yield was predicted. Curved-line B
represents a plot that had received irrigations until the time of heading. About 10
days after heading, the water supply was depleted and the cumulative SDD
steadily increased. Curve C followed B until another irrigation was given late in
the season. Curves D and E had ample water until about 30 days after heading,
curve E received another irrigation at that time. Curve F represents a plot that
was not stressed for water. This figure demonstrated how canopy temperature
data can be used to track crop water stress and the effect of stress on yield.

The SDD concept was applied to red kidney beans by Walker and Hatfield
(1979). They found that final yield was inversely related to the SDD, in agree-
ment with the results of Idso *et al.* (1977), and concluded that the SDD was a
valid representation of the effect of moisture stress on yield. They plotted the
total amount of water used (measured with a neutron moisture meter) as a
function of accumulated SDDs. Results are shown in Fig. 5, which demonstrates
that the less water available for transpiration, the higher the SDD. These data
provide evidence that transpiration and canopy temperatures are related, a fact
that was difficult to establish for leaf temperatures by short-term experiments
(see Section II,A). The application of the SDD to irrigation scheduling was
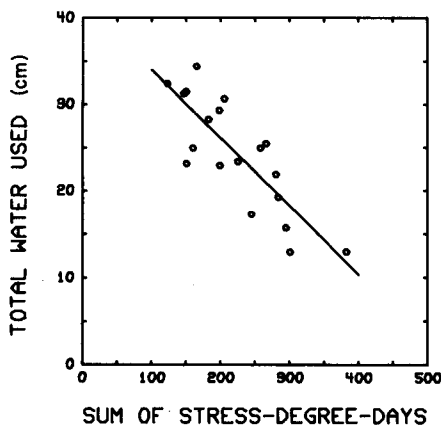suggested, but not demonstrated.

FIG. 5.   Seasonal water use as related to the summation of SDDs: slope, -0.0788; intercept,
41.84; $R = 0.822$. [Redrawn from Fig. 5 of Walker and Hatfield (1979, p. 970) by permission of the
authors and the American Society of Agronomy, Inc., 677 South Segoe Road, Madison, WI 53711.]

Jackson *et al.* (1977) evaluated the SDD as a possible irrigation-scheduling tool. They measured water depletion with a neutron moisture meter, and accumulated all positive values of the SDD. Whenever the SDD was negative, it was taken to be zero. Results for two plots are shown in Fig. 6. Numerical values on the ordinate refer both to the positive SDDs and centimeters of water depleted. It was concluded that irrigations should be given when or before the positive SDDs reached a value of 10.

Evapotranspiration (ET) calculated using canopy temperatures was compared with ET measured by weighing lysimeters and soil water depletion by Jackson *et al.* (1977). They found that the empirical relation

$$ET = R_n - 0.064(T_c - T_A) \tag{5}$$

would describe ET for periods of a week or more, but not for individual days. In Eq. (5) R_n is the net radiation. The temperature measurements were taken at one time of day (postnoon), whereas the ET is given in cm day^{-1}. They found that net radiation could be estimated with sufficient accuracy to yield reliable values of ET. These results support the suggestions of Stone and Horton (1974): that net radiation could be estimated from incoming solar radiation and albedo, that air temperatures could be determined on the ground, and that airborne scanners
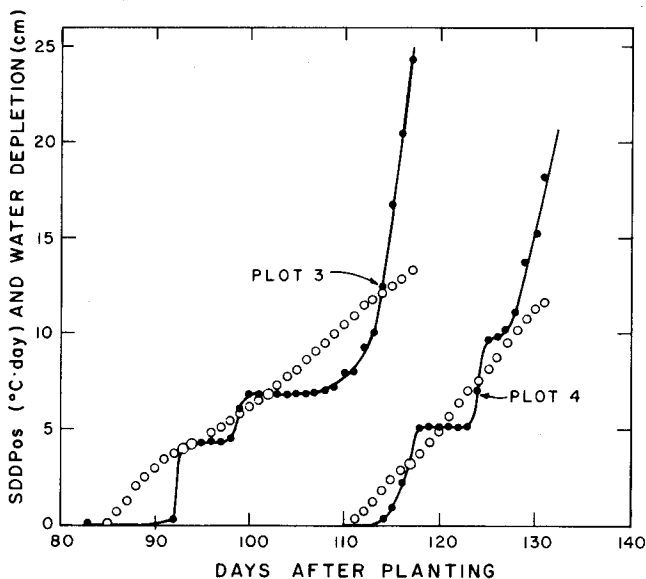

FIG. 6.   Positive SDDs (-•-) and water depletion (o) as a function of days after planting for two wheat plots. The summation was set at zero at the last irrigation. Numerical values on the ordinate are the same for both factors (from Jackson *et al.*, 1977).

could be used to measure T_c, enabling water use by crops to be evaluated over large areas.

Sequin and Petit (1980) calculated ET for a dry and an irrigated zone in southern France using four methods, two of which used remotely sensed surface temperature as an input. One of the methods was the simplified approach of Jackson et al. (1977). They concluded that the temperature methods gave satisfactory results, with a precision of 10–15% compared to an energy balance reference method. The advantage of the simplified approach is that neither extensive ground measurements nor the evaluation of surface roughness is necessary.

Heermann and Duke (1978) used the average temperature difference between treatment plots and adjoining well-watered areas to study crop water stress under limited irrigation. Their plots were in a cornfield irrigated by sprinkler from a center-pivot system. The average temperature elevation was linearly related (with a negative slope) to applied water and to relative dry-matter yield. They concluded that an average temperature difference of greater than 1.5°C was significantly correlated with a reduction in yield.

The canopy–air temperature difference was combined with net radiation and vapor pressure data and used as an irrigation-scheduling tool by Geiser et al. (1982). They compared the temperature method with resistance blocks and a checkbook method and concluded that irrigation water use was less when the temperature difference was used as the scheduling criterion.

Blad et al. (1981), Clawson and Blad (1982), and Gardner et al. (1981a) built on the suggestion of Aston and Van Bavel (1972) and tested the deviation of midday canopy temperature for usefulness as an irrigation-scheduling tool. They found standard deviations of 0.3°C in fully irrigated plots of corn. In nonirrigated plots, the standard deviation was as great as 4.2°C. They concluded that plots which exhibited a standard deviation above 0.3°C were in need of irrigation. Figure 7, taken from Clawson and Blad (1982), shows the daily values of canopy temperature variability (CTV), defined as the range (maximum minus minimum) of all IR thermometer-sensed temperatures within a plot during a particular measurement period. For this plot, irrigations were given when the CTV reached a value of 0.8.

Figure 8, also taken from Clawson and Blad (1982), shows the difference in temperature between a stressed plot and a well-watered plot [called the *temperature stress day* (TSD) by Gardner et al. (1981b)]. Use of the well-watered plot as a reference compensates for environmental effects such as air temperature and vapor pressure deficit. For the data shown in Fig. 8, irrigations were given when the average of all canopy temperatures measured in the stressed plot during a particular time period were 1°C warmer than the average canopy temperatures of the well-watered plot. These experiments indicate that both methods, the CTV and the TSD, could be used as a viable irrigation-scheduling technique.

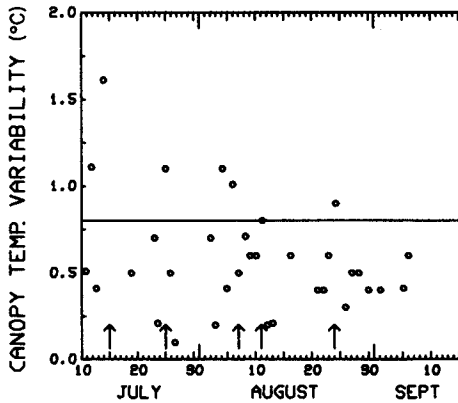The SDD as used by Jackson et al. (1977) proved insufficient to assess water

FIG. 7.   Canopy temperature variability of corn during the growing season. The critical CTV was set at 0.8 for this treatment. Arrows indicate irrigations [after Clawson and Blad (1982), by permission of the authors and the American Society of Agronomy, Inc., 677 South Segoe Road, Madison, WI 53711].

stress in corn. Gardner *et al.* (1981a) showed that stressed corn plants were below air temperature much of the time and suggested that corn may be more sensitive to water stress than wheat. They also suggested that canopy–air temperature differences may be soil, crop, and climate specific.

Gardner *et al.* (1981b) plotted the fraction of the maximum yield as a function
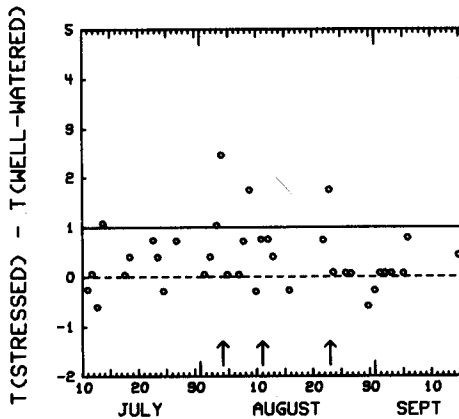

FIG. 8.   Canopy temperature differences between a stressed and well-watered corn plot. The critical value of the TSD for this treatment was 1. Arrows indicate irrigations [after Clawson and Blad (1982), by permission of the authors and the American Society of Agronomy, Inc., 677 South Segoe Road, Madison, WI 53711.]

of the TSD for two varieties of sorghum. They found a quadratic relationship between yield and TSD, in contrast to the linear relation between yield and the SDD found by Idso *et al.* (1977). The possibility of using canopy temperatures to predict the growth stage of corn was investigated by Gardner *et al.* (1981c). They found that the summation with time of the canopy temperature was highly correlated with growth stage, but that indices developed as stress indicators (e.g., canopy–air temperature difference) were not well correlated.

b. Plant Water Potential. The assumption that canopy temperature is a measure of plant water stress is largely based on qualitative observations such as visual wilting. Physiological processes are often affected before wilting becomes apparent, and different species may wilt at different stress levels (Hsiao, 1973). Since plant water potential has gained wide acceptance as a fundamental measure of plant water status, it is of interest to compare such measurements with canopy temperature data.

The plant water potential can be measured by use of a pressure chamber such as that described by Scholander *et al.* (1965). Either whole plants or parts of plants can be measured, depending upon plant size and species and the chamber size. With plants such as cotton, a leaf with petiole is usually measured, whereas with grain, the entire above-ground portion of the plant may be placed in the chamber. In either case the sample measured is a small part of an entire canopy, and considerable variation is to be expected.

Plant water potentials were measured on whole (above-ground) wheat plants on 19 clear days (at 1400 hr) at Phoenix, Arizona, by Ehrler *et al.* (1978a). Canopy temperatures were measured concurrently, using IR thermometers. Measurements were made on six differently irrigated plots and the results are shown in Fig. 9. Even with a number of observations per plot, there was a considerable amount of scatter in the data. The line drawn through the points indicated that as stress increased (plant water potential decreased), the canopy–air temperature difference increased. The temperature difference reached a maximum of about 5°C and increased only slightly with further decrease in plant water potential. Data of Sumayao *et al.* (1980), if plotted on Fig. 9, would fall well within the range of values shown for wheat. One can conclude from these data that canopy temperatures and plant water potential are indeed correlated, but not linearly, and that variability due to sampling precludes a more quantitative comparison.

The diurnal change in plant water potential and canopy temperatures was documented for wheat by Ehrler *et al.* (1978b). The diurnal range of plant water potential was considerable, from about -0.1 to -1.6 MPa for well-watered plots, and from about -2.1 to -4.3 MPa for a water-deficient plot. They concluded that for canopy temperature measurement, 1400 hr was the best time of day to assess water stress, a conclusion also reached by Blad *et al.* (1981).
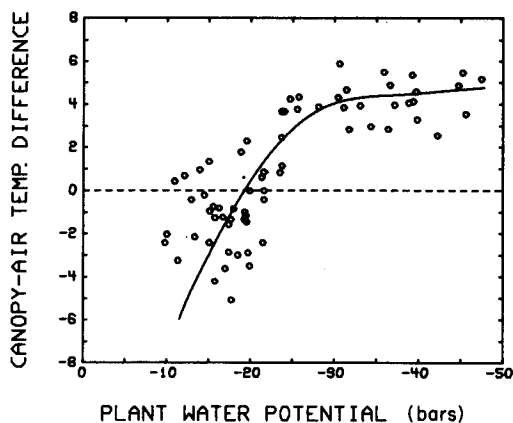
FIG. 9. Temperature of the canopy minus the air temperature at 1.5 m above the crop at 1400 as affected by the whole-plant water potential, the data consisting of 70 points from measurements taken on 19 clear days, with each point being the mean of 12-30 pressure chamber readings on separate plants, and 4-12 ΔT readings. The 70 points were derived from 220 individual sets of data (after Ehrler *et al.*, 1978a).

Heermann and Duke (1978) measured plant water potentials prior to dawn in conjunction with postnoon temperature measurements in corn. They found no trend in the plant water potential measurements for different water application rates, but observed significant yield reductions. Gardner *et al.* (1981b) compared the difference in plant water potential between stressed and nonstressed sorghum and the canopy temperature difference between the two plots. They found a parabolic relation between the two differences, i.e., the potential difference increased with an increase in the temperature difference to a maximum at about 4°C, then decreased. They recognized the effect of measurement variability and suggested that stomatal opening and closing may affect relationships between canopy temperature and plant water potential.

A general conclusion reached by considering the above results is that a quantitative measure of plant water stress under field conditions has not been achieved. The variability of point measurement of plant properties such as water potential is considerable. A canopy temperature measurement may be a better indicator of plant water stress, at least during the early stages of stress. As the canopy becomes several degrees warmer than the air, the temperature difference becomes insensitive to changes in plant water potential.

c. *Environmental Factors.* Changing cloud conditions can dramatically affect canopy temperatures. Measurements made under such conditions will increase data variability. Wiegand and Namken (1966) reported leaf-temperature changes of up to 6°C caused by changing solar insolation. Leaves required 30-45

sec to reach a new equilibrium after being shaded by a cloud. Blad *et al.* (1981) reported leaf temperature changes of 5.2°C in stressed corn, but only a 3.6°C change in nonstressed corn. They suggested that quantification of stress would be difficult under conditions of variable cloudiness.

Leaf temperature decreased with increased wind speed in wind-tunnel experiments of Barthakur (1975). He found the greatest variation to occur at wind speeds of 0-2 m sec^{-1}. Beyond 2 m sec^{-1} leaf temperatures were not significantly affected by increases in wind speed. Carlson *et al.* (1972) did not show a significant effect of wind speed on the temperature of soybean leaves under field conditions. Okuyama (1975) measured rice canopy temperatures with an IR thermometer. His data show no trend in canopy–air temperature differences with wind speeds ranging from 0.2 to 1 m sec^{-1}. From these results it can be assumed that wind will affect canopy temperatures, but in a minor way.

III. Quantification of Crop Water Stress

A review of the meterological, soil, and plant factors that are used to signal irrigation needs shows that whereas meterological and soil factors indicate when plants *may* be stressed, plant factors indicate when they *are* stressed. Plant factors, such as water potential, are point measurements that require numerous samples to characterize a field. Canopy temperature measurements can minimize this problem. Up till now, however, canopy temperature techniques have not been entirely satisfactory for quantifying plant water stress.

Three temperature indices have been proposed in the literature: the SDD, which is the canopy–air temperature difference measured postnoon near the time of maximum heating; the TSD, which is the difference in canopy temperatures between a stressed crop and a nonstressed (well-watered) reference crop; and the CTV, which is the range of temperatures encountered when measuring a plot during a particular measurement period.

With the SDD, plants were considered stressed if the value was positive and not stressed if negative. Experimental evidence has shown that the arbitrary division of SDD = 0 is not appropriate for all environmental conditions. The TSD requires a reference plot that is *not stressed* to be in close proximity to the field in question. The critical CTV value to be used as a signal to irrigate may be influenced by the degree of variability of soil properties inherent within a field.

The combined energy balance–aerodynamic relation used to predict evaporation from natural surfaces (Penman, 1948) can be written with the surface temperature as a function of net radiation and vapor pressure deficit (Monteith and Szeicz, 1962). This approach leads to a temperature-based stress index that may prove to be a reliable means of quantifying crop water stress. The following development is based on Jackson *et al.* (1981).

A. Energy Balance Considerations

The energy balance for a crop canopy can be written

$$R_n = G + H + \lambda E \tag{6}$$

where R_n is the net radiation (W m^{-2}), G is the heat flux below the canopy (W m^{-2}), H is the sensible heat flux (W m^{-2}) from the canopy to the air, λE is the latent heat flux to the air (W m^{-2}), and λ is the heat of vaporization. In their simplest forms, H and E can be expressed as

$$H = \rho c_p (T_c - T_A)/r_a \tag{7}$$
$$\lambda E = \rho c_p (e_c^* - e_A)/[\gamma(r_a + r_c)] \tag{8}$$

where ρ is the density of air (kg m^{-3}), c_p is the heat capacity of air (J kg^{-1} °C^{-1}), T_c is the surface temperature (°C), T_A is the air temperature (°C), e_c^* is the saturated vapor pressure (Pa) at T_c, e_A is the vapor pressure of the air (Pa), γ is the psychrometric constant (Pa °C^{-1}), r_a is the aerodynamic resistance (sec m^{-1}), and r_c is the canopy resistance (sec m^{-1}) to vapor transport. A detailed discussion of procedures and assumptions leading to Eqs. (6)–(8) was given by Monteith (1973).

Combining Eqs. (6)–(8), assuming that G is negligible and defining Δ as the slope of the saturated vapor pressure-temperature relation $(e_c^* - e_A^*)/(T_c - T_A)$ in units of Pa °C^{-1}, we obtain

$$T_c - T_A = \frac{r_a R_n}{\rho c_p} \cdot \frac{\gamma(1 + r_c/r_a)}{\Delta + \gamma(1 + r_c/r_a)} - \frac{e_A^* - e_A}{\Delta + \gamma(1 + r_c/r_a)} \tag{9}$$

which relates the difference between the canopy and the air temperatures to the vapor pressure deficit of the air $(e_A^* - e_A)$, the net radiation, and the aerodynamic and crop resistances. Equation (9) was given in a slightly different form by Monteith and Szeicz (1962). The upper limit of $T_c - T_A$ can be found from Eq. (9) by allowing the crop resistance r_c to increase without bound, i.e., as $r_c \rightarrow \infty$

$$T_c - T_A = r_a R_n/\rho c_p \tag{10}$$

The lower bound, found by setting $r_c = 0$ in Eq. (9) (the case of wet plants acting as a free water surface), is

$$T_c - T_A = \frac{r_a R_n}{\rho c_p} \cdot \frac{\gamma}{\Delta + \gamma} - \frac{e_A^* - e_A}{\Delta + \gamma} \tag{11}$$

Equations (9) and (11) describe a linear relation between $T_c - T_A$ and the vapor pressure deficit $e_A^* - e_A$. Thus, for a particular temperature, the lower

bound is a line extending from the intercept at $e_X^* - e_A = 0$ (saturated air) to a value of $e_X^* - e_A = e_X^*$ (completely dry air). The upper bound is independent of vapor pressure and dependent only on r_a and R_n. The bounds are shown by the lines labeled 0 (lower) and ∞ (upper) in Fig. 10. Lines for intermediate values of r_c (5, 50, and 500 sec m^{-1}) are also shown. All lines in this figure were calculated for a temperature of 30°C, and net radiation of 600 W m^{-2}

1. Aerodynamic and Canopy Resistances

In Eqs. (9)–(11) a value of r_a is needed. Reported values of r_a generally exceed 20 sec m^{-1} (Van Bavel and Ehrler, 1968; Szeicz and Long, 1969; Szeicz et al., 1969). These values were obtained using aerodynamic methods. Using $r_a = 20$ sec m^{-1} and $R_n = 600$ W m^{-2} in Eq. (10) yields $T_c - T_A = 10$°C, a rather high average temperature for a crop canopy, even when transpiration is zero. Before further discussion of Fig. 10, it will be necessary to establish a reasonable value of r_a.

Jackson et al. (1981) evaluated r_a for wheat by measuring T_c, T_A, and R_n for a mature, fully senesced wheat crop (with no available soil water), and then solving Eq. (10) for r_a. Measurements involved monitoring one area with a fixed-position 15°-field-of-view (FOV) IR thermometer and a hand-held 3°-FOV instrument. The stationary instrument was automatically scanned every 6 sec, with these values averaged over a 6-min period. With the hand-held instrument, 6–8 instantaneous measurements were made over different parts of the field. The temperature differences ranged from 2 to 9°C, and averaged 5° in both cases. The
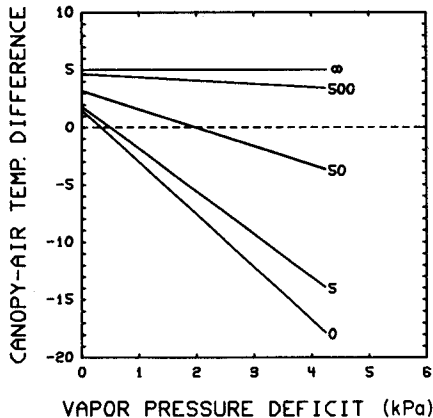

FIG. 10.   Theoretical relationship between the canopy–air temperature difference and the vapor pressure deficit. Numbers at the end of lines indicate the value of the canopy resistance r_c used for the calculations. All calculations were for an air temperature T_A of 30°C, net radiation R_n of 600 m^{-2}, and an aerodynamic resistance r_a of 10 sec m^{-1} (after Jackson, 1981).

wide range of temperatures was apparently due to the instability of the air within the canopy. With the radiometer held stationary, $T_c - T_A$ values were observed to increase until a value of about 9°C was reached; then they dropped rapidly to about 2°C. During the measurements the wind speed was low (1 m sec^{-1} or less), the incoming radiation was high ($\simeq 800$ W m^{-2}), and the air temperatures were >35°C, conditions conducive to high canopy temperatures. Since the average value of $T_c - T_A$ was 5°C under these conditions (and those of Ehrler *et al.*, 1978a), this value may be near the maximum that can be expected. With 5°C in Eq. (10), $r_a = 10$ sec m^{-1}.

Idso *et al.* (1981b) obtained $T_c - T_A$ and $e_A^* - e_A$ data for well-watered alfalfa fields located in Arizona, Kansas, Minnesota, and Nebraska, and for a stressed alfalfa field in Arizona (Fig. 11). The intercept of a $T_c - T_A$ versus $e_A^* - e_A$ plot for water-stressed alfalfa was about 1°C. Since r_c was finite, Eq. (10) does not apply, but the first term on the right-hand side of Eq. (11) can be used to estimate r_a. The resulting value is 6 sec m^{-1}. A likely value for r_a probably lies between 6 and 10 sec m^{-1}, and this value may be relatively constant.

In the above discussion, r_a was established for unstable conditions, i.e., the canopy was warmer than the air. When the canopy is cooler than the air, r_a may be greater (Szeicz and Long, 1969). A sensitivity analysis of Eq. (9) showed that $T_c - T_A$ was most affected by changes in r_a at low values of the vapor pressure deficit. For larger values of the deficit (3–5 kPa), increasing r_a by a factor of 3 had little effect on $T_c - T_A$.

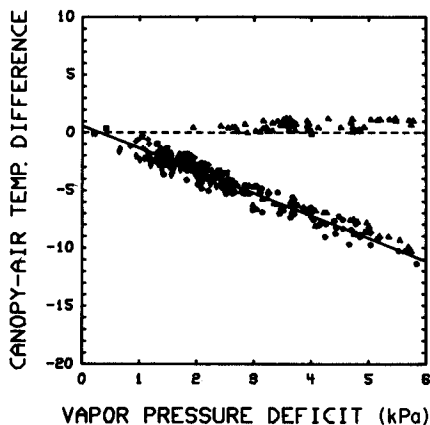The lines in Fig. 10 were calculated for several values of the canopy resistance

FIG. 11. Canopy–air temperature differences versus vapor pressure deficit for several well-watered plots of alfalfa assumed to be transpiring at the potential rate, and one severely water-stressed plot for which all temperature differences were positive: slope, −1.96; intercept, 0.58; $R = 0.95$. (After Idso *et al.*, 1981b.)

r_c. In this discussion, r_c is used to describe the overall resistance encountered within the soil–plant system by water moving to the leaf–air interface, from which it can evaporate. Components of this overall resistance are discussed by Van Bavel and Ehrler (1968). The lines shown in Fig. 10 extend from a completely saturated to a completely dry atmosphere, for an air temperature of 30°C. At 3 kPa, the temperature difference for a "wet" canopy would be about -12°C. With an increase of r_c to 5, 50, or 500 sec m^{-1}, the temperature difference would be, respectively, about -9.2°, -1.7°, or 3.8°C. These values indicate that, in a relatively dry environment, canopy–air temperature differences of 10–15°C could be expected, depending upon the degree of water stress of the crop. In a humid environment, canopy–air temperature differences would be much smaller, and would become positive for many situations. Thus, Eq. (9) and Fig. 10 partially explain the controversy that has raged for years over whether or not leaf temperatures should always be warmer than air.

2. *Experimental Verification*

The experimental results of Idso *et al.* (1981b), shown in Fig. 11, were obtained at five locations during the summer of 1980. All measurements were made under generally clear sky conditions, with canopy temperatures measured at intervals varying from 10–30 min at 2–3 hr before sunrise to 2–3 hr before sunset. At all sites the alfalfa was well watered and was assumed to be transpiring at the potential rate. Air temperatures ranged from about 20° to about 40°C during the course of the measurements.

Linear regression analysis of the data in Fig. 11 yielded the relation

$$T_c - T_A = 0.59 - 1.95(e_A^* - e_A) \qquad (12)$$

The slope (-1.95 °C kPa^{-1}) was somewhat smaller than for the leaf–air temperature, versus vapor pressure deficit relation (-1.29 °C kPa^{-1}) of Ehrler (1973), shown in Fig. 1. Since Ehrler (1973) measured leaf temperatures of cotton, whereas Idso *et al.* (1981b) measured canopy temperatures of alfalfa, we would not expect their slopes to be equal.

The scatter of data around the regression line in Fig. 11 may be due to net radiation changes, wind speed effects, and experimental errors involved in measuring the canopy, wet-bulb, and dry-bulb temperatures.

The linearity of the data lends validity to the assumptions underlying the development of Eq. (9) and to the assumption of a constant value of r_a. A comparison of Fig. 10 and 11 shows that a value of r_c between 10 and 20 sec m^{-1} would be necessary in Eq. (9) to predict the experimental temperatures at 3 kPa. However, the intercept of the experimental line (0.59) is less than any shown in Fig. 10. One explanation for this apparent discrepancy is that the lines in Fig. 10 were calculated assuming a constant air temperature of 30°C. The slope of the saturated vapor pressure–temperature relation (Δ) is a function of temperature.

Since Δ appears in both the slope and the intercept of Eq. (9), both terms are temperature dependent. Thus, the temperature-dependent lower bound is formed by a family of lines, one for each temperature. The result is a curved lower bound, as shown in Fig. 12. The symbols represent the end points of imaginary lines for temperatures incremented by 1° from 0° to 35°C. Lines for three of the temperatures (10°, 20°, and 30°C) are illustrated in the figure.

The lower limit shown by the plus signs in Fig. 12 is for a completely dry atmosphere, a situation not usually encountered. Also, in calculating this limit, various factors such as net radiation and resistance terms were held constant. In a natural situation the air is not completely dry, and the various environmental factors are all interrelated. Thus a curved lower limit may not be encountered in practice to the extent shown by Fig. 12, but a nearly linear relation, as observed experimentally by Idso *et al.* (1981c), may prevail over much of the vapor pressure deficit range. The situation for humid conditions is complicated by the fact that small temperature difference need to be measured.

3. *Potential Evapotranspiration*

Equation (11) represents the case of evaporation from a free water surface, which is not necessarily the case for potential evaporation from a crop. In irrigated areas the soil may be adequately supplied with water, yet the plant surfaces may appear dry. In this case the canopy resistance is probably not zero (Van Bavel and Ehrler, 1968), but has a value that will be called the *canopy resistance at potential evapotranspiration* r_{cp}. The value of r_{cp} will probably
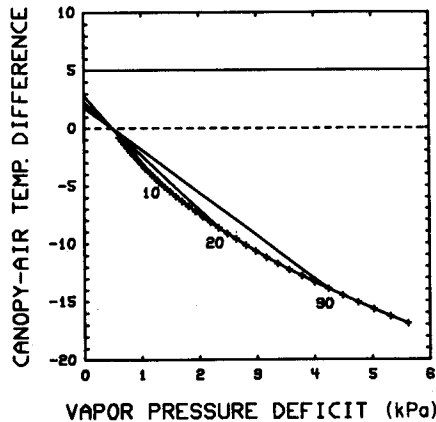

FIG. 12. The lower bound of the canopy-air temperature difference. The symbols represent the lower bound for a particular temperature at the maximum vapor pressure deficit for that temperature. Numbers identify the temperatures (°C) for the three straight lines. Other parameters were $r_a = 10$ sec m^{-1}, $r_c = 5$ sec m^{-1}, $R_n = 600$ W m^{-2} (after Jackson *et al.*, 1981).

be different for different crops, and may change with environmental conditions during a single day. Setting $r_c = r_{cp}$ in Eq. (9) we have

$$T_c - T_A = \frac{r_a R_n}{\rho c_p} \cdot \frac{\gamma^*}{\Delta + \gamma^*} - \frac{e_A^* - e_A}{\Delta + \gamma^*} \tag{13}$$

where

$$\gamma^* = \gamma(1 + r_{cp}/r_a) \tag{14}$$

4. An Index of Crop Water Status

A crop with adequate water will transpire at the potential rate for that crop. As water becomes limiting, the actual ET will fall below the potential rate. A measure of the ratio of actual to potential ET should, therefore, be an index of crop water status. Combining Eqs. (6)–(8) and solving for λE yields

$$\lambda E = \frac{\Delta R_n + \rho c_p(e_A^* - e_A)/r_a}{\Delta + \gamma(1 + r_c/r_a)} \tag{15}$$

which is the Penman–Monteith equation for ET in terms of canopy and aerodynamic resistances (Monteith, 1973; Thom and Oliver, 1977). Taking the ratio of actual (λE for any r_c) to potential (λE_p for $r_c = r_{cp}$) gives

$$\frac{E}{E_p} = \frac{\Delta + \gamma^*}{\Delta + \gamma(1 + r_c/r_a)} \tag{16}$$

with γ^* defined by Eq. (14). Jensen (1974) and Howell *et al.* (1979) discussed Eq. (16) for the case of $r_{cp} = 0$, i.e., $\gamma^* = \gamma$. Rearranging Eq. (16) will give r_c in terms of E/E_p, a result reported by Van Bavel (1967), Szeicz and Long (1969), and Russell (1980), again with $r_{cp} = 0$. Van Bavel measured E with lysimeters and calculated the canopy resistance.

The ratio E/E_p ranges from 1 (ample water, $r_c = r_{cp}$) to 0 (no available water, $r_c \to \infty$). In studying plant-water relations one thinks of a plant as going from a no-stress to a stressed condition. Therefore, it is esthetically pleasing for a stress index to go from 0 to 1. We consequently define a crop water stress index (CWSI) as

$$\text{CWSI} = 1 - \frac{E}{E_p} = \frac{\gamma(1 + r_c/r_a) - \gamma^*}{\Delta + \gamma(1 + r_c/r_a)} \tag{17}$$

To calculate the CWSI or E/E_p using Eqs. (16) or (17) requires a value for the ratio r_c/r_a. This is obtained by rearranging Eq. (9) with the result

$$\frac{r_c}{r_a} = \frac{\gamma r_a R_n/(\rho c_p) - (T_c - T_A)(\Delta + \gamma) - (e_A^* - e_A)}{\gamma[(T_c - T_A) - r_a R_n/(\rho c_p)]} \tag{18}$$

giving the ratio r_c/r_a in terms of net radiation, canopy and air temperatures, vapor pressure deficit, and the aerodynamic resistance. In practice, r_c/r_a is evaluated using Eq. (18) and substituted into Eq. (17) to obtain the CWSI.

A graphic representation of the CWSI is given in Fig. 13. With $r_a = 10$ sec m^{-1} and $R_n = 600$ W m^{-2}, the upper bound at $T_c - T_A = 5$ is obtained. If $T_A = 30°C$ and $r_c = 5$ sec m^{-1}, the lower bound is obtained. The canopy temperature is found by experiment to be 27°C. The difference, $T_c - T_A = -3$, is plotted at point B. A vertical line is extended from point B to the upper (point A) and the lower (point C) bounds. The CWSI is BC/AC = $[-3 - (-9.3)]/[5 - (-9.3)]$ = 0.44. The ratio of actual to potential ET [Eq. (16)] is AB/AC = 0.56.

The data shown in Fig. 11 indicate that a linear lower bound would obtain for well-watered conditions. Idso *et al.* (1981b) proposed that this lower bound (or baseline) be determined experimentally for a number of crops. This procedure is simpler in that a linear equation is used to determine $T_c - T_A$ at point C, instead of the more complicated calculations required by Eqs. (17) and (18). The empirical baseline, however, does not account for changes in net radiation, nor wind speed.

a. The Evaluation of Δ. The slope of the saturated vapor pressure–temperature relation Δ appears in most of the equations in the previous section. As a first approximation, Δ can be evaluated at the air temperature T_A. When the temperature difference $T_c - T_A$ is large (as for the case of well-watered crops at high vapor pressure deficits), a better approximation is to evaluate Δ at
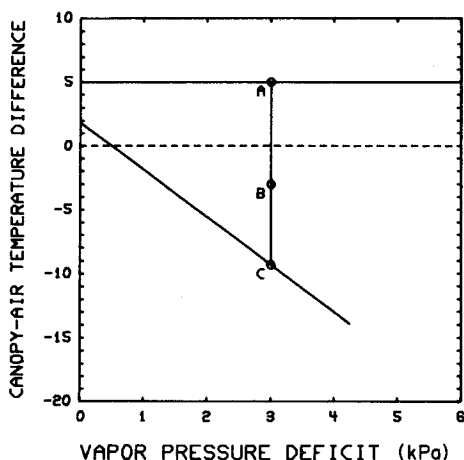

FIG. 13. A graphical representation of the CWSI calculation. Pertinent data are $r_a = 10$ sec m^{-1}, $R_n = 600$ W m^{-2}, $r_c = 5$ sec m^{-1}, $T_A = 30°C$, and $T_c = 27°C$.

$(T_c + T_A)/2$. Obviously, when T_c is near T_A the two approaches yield similar results. Taking the average of the canopy and air temperatures is sufficient for Eqs. (9), (11), (12), and (18), but Eqs. (16) and (17) pose a problem. Following closely the development of Eq. (16) from Eq. (15), we find that Δ in the numerator should be evaluated as the average of the air temperature and the canopy temperature that would obtain if the crop were evaporating at potential. The Δ in the denominator should be evaluated as the average of the actual measured canopy temperature and the air temperature. Keeping Δ as the value at the measured temperatures and Δ^* as the value using the calculated canopy temperature at potential, the numerator of Eq. (16) becomes $\Delta^* + \gamma^*$ and the numerator of Eq. (17) becomes $\gamma(1 + r_c/r_a - \gamma^* + \Delta - \Delta^*$.

The evaluation of Δ^* is complicated by the fact that T_c at potential may not be known. This can be estimated using an iterative procedure with Eq. (13) by evaluating Δ at T_A, calculating T_c, evaluating a new Δ at $(T_c + T_A)/2$, and recalculating T_c until an acceptable value is obtained. In practice, the use of Eqs. (16) and (17) with Δ evaluated at the average of the measured canopy temperature and the air temperature will yield similar results for both the low and high values of the indices, with the maximum error occurring near 0.5. At the midpoint, the difference between the two methods of calculation will be within 0.06, e.g., 0.48 for the one value of Δ and 0.54 when Δ and Δ^* are used. The results reported here are in terms of Δ evaluated at the average of the measured canopy and air temperatures.

b. The Effect of Wind. Wind is the only major environmental variable not explicitly appearing in Eq. (17). It is, however, implicit in that it affects the aerodynamic resistance r_a (Van Bavel and Ehrler, 1968). Thom and Oliver (1977) derived a wind function for Penman's evaporation equation. In terms of the aerodynamic resistance it is

$$r_a = \frac{4.72[\ln(z - d)/z_0]^2}{1 + 0.54U} \tag{19}$$

where z is the height above the surface, d the displacement, z_0 is the roughness parameter, and U is the wind speed in m sec^{-1}. This relation shows that r_a is inversely related to a linear function of wind. With Eqs. (9)–(11) and (17), some qualitative observations concerning the effect of wind on $T_c - T_A$ can be made. For the case of a wet surface evaporating as a free water surface ($r_c = 0$), Eq. (11) shows that r_a appears only in the first term on the right-hand side. If wind speed were to increase, the intercept of the lines shown in Fig. 10 would decrease. The net result would be a slight lowering of $T_c - T_A$ with increasing wind for all values of the vapor pressure deficit. At the upper limit, Eq. (10) shows that $T_c - T_A$ would vary greatly with r_a and tend toward, but not reach, zero as the wind speed increases. For the intermediate region ($r_c > 0$), $T_c - T_A$

may increase or decrease with wind speed, depending on the values of r_a and r_c (with constant values for the net radiation and the vapor pressure deficit). This complex interaction shows the need for specific experiments to elucidate the effect of wind because, in a natural environment, an increase in wind speed changes not only r_a but also r_c, T_A, and possibly $e_A^* - e_A$ in a manner not easily calculable.

B. EXPERIMENTAL ASPECTS

Although the CWSI is based upon well-known principles, its very recent development means that the experimental data available for its evaluation are limited. A preliminary evaluation can be made with the data presented by Jackson et al., (1981) and Jackson (1981). The following discussion is based largely on their work.

1. Procedure

Wheat (*Triticum durum* Desf. var. Produra) was planted in 11 × 13-m plots on 6 February 1980 (Julian day 37), and first irrigated on 8 February. Plot A received a second irrigation on 9 April (day 100). Plot B was irrigated on 2 April (day 93) and 23 April (day 114). Plot C, the wettest treatment, received a second irrigation on 19 March (79), a third on 15 April (106), a fourth on 2 May (123), and a fifth on 13 May (134). All irrigations were in the range of 0.10–0.12 m of water.

Canopy temperatures were measured with a portable IR thermometer held at an angle of about 30° from horizontal. By the time the plants were about 0.2-m tall (day 70), the instrument predominantly viewed plants. Plot canopy temperatures were taken as the average of eight measurments, four facing east and four facing west (to minimize sun angle effects). Wet- and dry-bulb temperatures were measured with a psychrometer held at a height of 1.5 m. Incoming solar radiation was recorded, from which net radiation was estimated.

Soil water contents were measured with a neutron soil moisture meter in each plot at 0.2-m intervals to a depth of 1.6 m, two to three times per week. Water contents for each depth were smoothed using a sliding cubic technique (an adaptation of the sliding parabola of DuChateau et al., 1972). The smoothing procedure allowed the interpolation of water contents for each day.

The traditional way to determine the amount of "available" water is to calculate the amount held at "field capacity" and subtract the amount held at the "wilting point" (as estimated by a laboratory measurement that determines the water remaining in the sample after being subjected to 1.5 MPa of air pressure). Ritchie (1981) proposed that "extractable" water is a more precise measure of water availability to plants because the measurements are made *in situ*. This can be done by measuring the water content of a full soil profile (with an actively

growing, fully developed crop) shortly after irrigation (taking drainage into account). This is called the drained upper limit. The lower limit is determined by withholding water from the crop after the root system has developed and then, when the plants have died, measuring the profile water content. The extractable water is the difference between the two profile measurements. Ritchie (1981) suggested that it be measured for each soil and each crop.

The drained upper limit and the lower limit for the wheat plots were measured. The total extractable water to a soil depth of 1.1 m was found to be 0.175 m. The fraction of extractable water used to that depth was calculated from the smoothed water content data.

2. *The Crop Water Stress Index and Soil Water*

Measured data for the CWSI are shown in Fig. 14. Lines were drawn through the points by eye. The data show the day-to-day change in CWSI in addition to the scatter that might be expected due to errors in measurements of canopy temperatures and wet- and dry-bulb air temperatures. The plus (+) symbols represent the fraction of extractable water used.

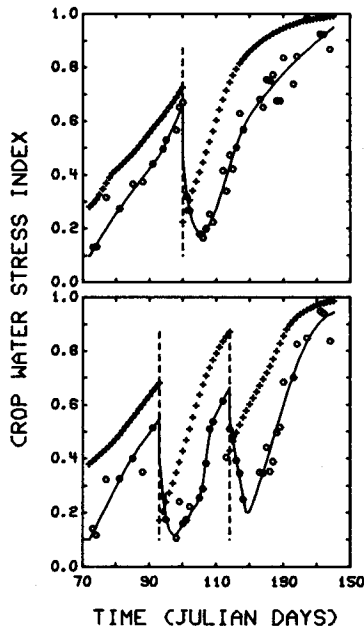The fraction of extractable water used increased with time, dropping to a

FIG. 14. The CWSI (circles represent data points) and the relative amount of extractable water used (plus symbols) as a function of Julian day for two wheat plots. Dashed vertical lines indicate irrigations (from Jackson, 1981).

minimum following irrigation (zero would indicate a full profile). The CWSI also increased with time, roughly in parallel with the extractable water used. At first glance, it appears that a reasonably good correlation exists between the two factors. However, it can be seen that the CWSI did not drop to its lowest value immediately after irrigation. Instead, the CWSI required 5-6 days to reach a minimum, implying that stressed wheat requires some time to recover (Hsiao, 1973). Some possible reasons for this are that leaves need to rehydrate and roots that were previously in dry soil need to develop new root hairs. The length of the recovery period depends largely upon the degree of stress experienced by the plants, but it may also vary with plant species and age. A similar recovery period has been documented for cotton by Ehrler (1973) and for sorghum by Idso and Ehrler (1976).

The existence of a recovery period for the temperature-based index is evidence that a unique relationship does not exist between plant temperatures and soil moisture. This is further demonstrated by plots of the CWSI versus extractable water used, as shown in Figs. 15 and 16. For plots A and B, the circles represent data after the first irrigation (at planting). These data are rather similar for both plots, the CWSI increasing in a linear manner with increasing amounts of ex-
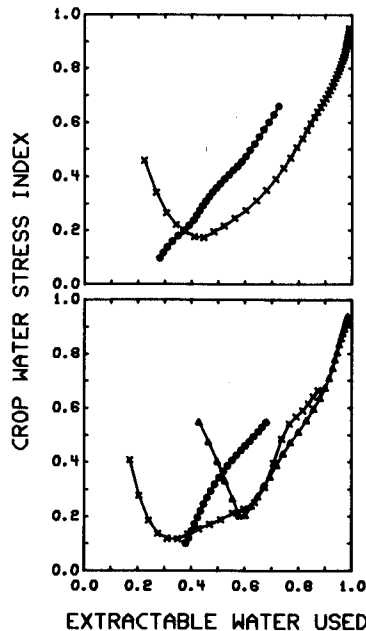

FIG. 15.   CWSI versus fraction of extractable water used for two wheat plots. Data after the first (●), second (×), and third (▲) irrigations (plot B only) (from Jackson, 1981).
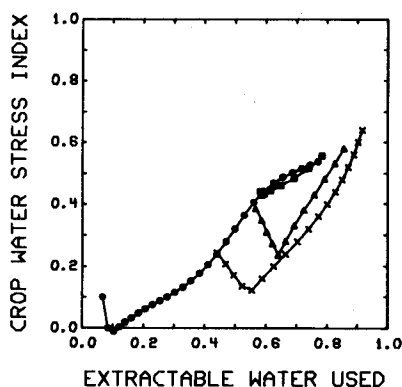
Fig. 16. CWSI versus relative amount of extractable water used for a wheat plot that received a total of five irrigations. Data after the second (●), third (×), fourth (▲), and fifth (■) irrigations (from Jackson, 1981).

tractable water used. The second irrigation was given to plot B seven days prior to the one given to plot A; thus plot A was the most stressed of the three plots. This point is also evident in the greater recovery time required for plot A as seen in Figs. 14–16. The wettest plot (Fig. 16) required nearly the same recovery time for the third (crosses) and fourth (triangles) irrigations as did plots A and B (Fig. 14). However, the second irrigation (circles) recovered in 1–2 days. This irrigation was given early in the season while the plants were actively growing and were not stressed. The fifth irrigation, given late in the season when much of the vegetation had senesced, showed no recovery period but also no decrease in the CWSI after irrigation.

The CWSI lines for each irrigation do not coincide with the values for a prior irrigation, even after the plants have recovered. This is further evidence that the relation between CWSI and soil moisture is not unique. This probably results, in part, from changes in rooting volume with time due to plant growth and the location of available water. The complexity of the situation becomes evident when one considers that soil water availability depends on root distribution, which, in turn, is determined predominantly by irrigation history (Chaudhary and Bhatnager, 1980) as well as by soil and aerial factors such as nutrient availability and evaporative demand. Since the precise rooting volume cannot be determined, exact correspondence of CWSI and extractable water should not be expected.

Another factor of importance that is evident in Fig. 16 (data for the fifth irrigation—squares) is the effect of plant senescence on the CWSI–extractable water relation. As the wheat matured, green leaves began to die, causing transpiration (with its consequent evaporative cooling) to decrease. Thus, after an irrigation, plant temperatures remained high (causing a high CWSI) even though the fraction of extractable water used was low.

3. *The Crop Water Stress Index and Crop Water Stress*

In order for the CWSI to be a useful irrigation-scheduling tool, its relation to crop water stress must be established. Attempts to relate other temperature indices to plant water stress have not been entirely satisfactory because of data variability (Section II,B,3b).

Recently, Pinter (1982) reviewed how reflected light in certain wave bands can be used to assess green biomass. As green plants begin to cover the soil, the reflection of visible red light is reduced because of absorption by plants. Near-IR light generally is reflected more by green plants than by soils. The ratio of the reflected near-IR to the visible red is therefore a sensitive indicator of green biomass.

Jackson and Pinter (1981) measured the reflectance of the near IR (0.8–1.1 μm) and the visible red (0.6–0.7 μm) over the same wheat plots (at the same time of day) as were used for the CWSI measurements, using a hand-held spectral radiometer (Jackson *et al.*, 1980). The near-IR : red ratio was formed, and the data are shown in Fig. 17 for the driest (plot A) and the wettest (plot C) treatments. From shortly after planting until about day 80, the ratios are essentially the same for the two plots. On day 79, plot C was irrigated. Within two days the ratio for plot C was markedly higher than for plot A. The data show that an irrigation at about day 80 (indicated by the arrow labeled INF) was critical if growth was to be maintained. Figure 14 shows that the CWSI was about 0.28 on day 80. The ratio reached a maximum for plot A on day 94, and for plot C on day 99. The maximum of the ratio is the point where new green growth is offset by senescence (indicated by the arrow labeled MAX). At the maximum ratio for
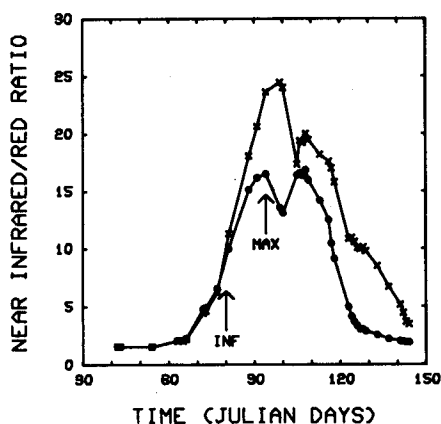

FIG. 17.   The ratio of near IR (0.8–1.1 μm) to red (0.6–0.7 μm) for plot C (crossed symbols) as a function of Julian data (from Jackson and Pinter, 1981).

both plots the extractable water used was about 0.67 and the CWSI was about 0.5.

These data suggest that if the CWSI becomes greater than 0.3, a reduction in growth rate is imminent. If it reaches 0.5, net growth will cease and may decrease. Irrigations should therefore be given when the CWSI is within the range 0.3–0.5, the precise value being determined by water availability and other management factors.

The above criteria were determined for wheat in the vegetative stage, using specific values of r_{cp} (5 sec m^{-1}) and r_a (10 sec m^{-1}). There is some indication that r_{cp} may increase with growth stage. Obviously, much research needs to be done before an operational system of irrigation scheduling using the CWSI is perfected.

IV. Concluding Remarks

"Leaf temperatures are always warmer than the air" is a statement that is still heard today. This concept stems from research done during the first half of this century, for the most part in humid regions and glasshouses. Reports of leaves being cooler than the air, such as the 7°C difference measured by Wallace and Clum (1938), were soon challenged by Curtis (1938). It is entirely possible that Curtis never measured a leaf that was cooler than the air. One only needs to look at Eq. (9) and Figs. 10 and 11 to see that in humid climates leaves are likely to be warmer than the air, especially when the leaf is sunlit and near the top of the plant.

The concept of leaves being warmer than air has persisted, and the suggestion that leaf or canopy temperatures could be used as an irrigation-scheduling tool is sometimes received with skepticism. However, it is now rather obvious that leaf and canopy temperatures may be either warmer or cooler than the air, depending upon environmental factors that can for the most part be specified.

Equation (9) and Figs. 10 and 11 also show the limitations of any temperature-based stress index. In humid climates canopy temperatures will be near to or higher than air temperatures, with only a small range of tamperatures. In arid areas, however, canopy temperatures may be more than 10°C below air temperature and have a range of perhaps of 15°C. It is in the arid areas where irrigation is practiced that temperature techniques can work best and are most needed. This does not preclude their use during dry periods in normally humid areas. With Eq. (9), and pertinent meterologoical data, the potential usefulness for temperature techniques can be ascertained.

All temperature-based stress indices assume that only vegetation temperatures are measured. With IR thermometry, care must be taken to avoid the complication of the soil background, especially when sparse vegetation is being measured.

This is a particular problem when airborne scanners are used over row crops that do not completely cover the soil. Some plant species will orient their leaves to be normal to incident sunlight if well watered and to be parallel to the light when stressed, with an apparent reduction of ground cover from 100% to about 20% (Byrne *et al.*, 1979). We need to know much more about how plant and canopy architecture affects canopy temperature measurements.

Critical values of the temperature indices need to be established for various crops. For example, a CWSI of 0.3 may be the critical value for wheat but not for cotton. Some evidence indicates that water stress prior to the bloom stage in cotton may reduce vegetative growth and save water, without reducing yields (Guinn *et al.*, 1981). Temperature measurements may not be a sufficient indicator of irrigation needs for potatoes grown for tuber quality on certain soils. In this case irrigations are given to keep the soil moist, facilitating tuber expansion, with the plants never stressed. These are but a few management factors that should be considered as the development of temperature-based indices progresses.

The tremendous advance in IR technology during the past few years has allowed the production of lightweight hand-held IR thermometers that can be used to measure plant canopy temperatures rapidly. Many of these instruments have just recently become available to agricultural researchers. Some have already been purchased by farmers and farm consultants. The next few years should see an explosion of knowledge about canopy temperatures and about how such information can be used in irrigation management. The timing of irrigations is the likely area for the maximum use of these instruments. The data accumulated so far strongly suggest success.

Even the casual reader of this review will easily discern the personal bias of the author. For this I do not apologize, but hope that enough information is presented so that the reader can evaluate the material objectively. In my opinion, agricultural application of remotely sensed temperatures (and other remote measurements) is just beginning. Much exciting research is in store.

References

Ansari, A. Q., and Lommis, W. E. (1959). Leaf temperatures. *Am. J. Bot.* **46,** 713–717.

Askenasy, E. (1875). Ueber die temperature welche pflanzen im sonnenlicht annehmen. *Bot. Zg.* **33,** 441–444.

Aston, A. R., and Van Bavel, C. H. M. (1972). Soil surface water depletion and leaf temperature. *Agron. J.* **64,** 368–373.

Barthakur, N. (1975). Leaf temperatures under controlled environmental conditions. *Int. J. Biometeorol.* **19,** 21–27.

Bartholic, J. F., Namken, L. N., and Wiegand, C. L. (1970). Combination equations used to

calculate evaporation and potential evaporation. *U.S. Agric. Res. Serv., ARS* **USDA-ARS-41-170,** 1–14.

Bartholic, J. F., Namken, L. N., and Wiegand, C. L. (1972). Aerial thermal scanner to determine temperatures of soils and of crop canopies differing in water stress. *Agron. J.* **64,** 603–608.

Bell, J. P. (1976). "Neutron Probe Practice," Inst. Hydrol. Rep. No. 19. Natural Environmental Research Council, Wallingford, England.

Blad, B. L., and Rosenberg, N. J. (1976). Measurement of crop temperature by leaf thermocouple, infrared thermometry, and remotely sensed thermal imagery. *Agron. J.* **68,** 635–641.

Blad, B. L., Gardner, B. R., Steinmetz, S., and Rosenberg, N. J. (1982). Plant and air temperature patterns in alfalfa, corn, grass, sorghum and soybeans as measured with thermocouples and infrared thermometers. *Agron. J.* (in press).

Blad, B. L., Gardner, B. R., Watts, D. G., and Rosenberg, N. J. (1981). Remote sensing of crop moisture status. *Remote Sens. Q.* **3,** 4–20.

Brown, K. W., and Rosenberg, N. J. (1973). A resistance model to predict evapotranspiration and its application to a sugar beet field. *Agron. J.* **65,** 341–347.

Byrne, G. F., Begg, J. E., Fleming, P. M., and Dunin, F. X. (1979). Remotely sensed land cover temperature and soil water status—A brief review. *Remote Sens. Environ.* **8,** 291–305.

Carlson, R. E., Yarger, D. N., and Shaw, R. H. (1972). Environmental influences on the leaf temperatures of two soybean varieties grown under controlled irrigation. *Agron. J.* **64,** 224–229.

Chaudhary, T. N., and Bhatnagar, V. K. (1980). Wheat root distribution, water extraction pattern and grain yield as influenced by time and rate of irrigation. *Agric. Water Manage.* **3,** 115–124.

Cihlar, J. (1976). "Thermal Infrared Remote Sensing: A Bibliography," Res. Rep. 76-1. Canada Center for Remote Sensing, Ottawa.

Clark, R. N., and Hiler, E. A. (1973). Plant measurements as indicators of crop water deficit. *Crop Sci.* **13,** 466–469.

Clawson, K. L., and Blad, B. L. (1982). Infrared thermometry for scheduling irrigation of corn. *Agron J.* **74** (in press).

Clum, H. H. (1926). The effect of transpiration and environmental factors on leaf temperatures. I. Transpiration. *Am. J. Bot.* **13,** 194–230.

Conaway, J., and Van Bavel, C. H. M. (1967a). Radiometric surface temperature measurements and fluctuations in sky radiant emittance in the 600 to 1300 cm^{-1} waveband. *Agron. J.* **59,** 389–390.

Conaway, J., and Van Bavel, C. H. M. (1967b). Evaporation from a wet soil surface calculated from radiometrically determined surface temperatures. *J. Appl. Meteorol.* **6,** 650–655.

Curtis, O. F. (1936). Leaf temperatures and the cooling of leaves by radiation. *Plant Physiol.* **11,** 343–364.

Curtis, O. F. (1938). Wallace and Clum, "Leaf temperatures": A critical analysis with additional data. *Am. J. Bot.* **25,** 761–771.

David, W. P. (1969). "Remote Sensing of Crop Water Deficits and its Potential Applications," Remote Sens. Cent. Tech. Rep. RSC-06. Texas A&M University, College Station.

DuChateau, P. C., Nofziger, D. L., Ahuja, L. R., and Swartzendruber, D. (1972). Experimental curves and rates of change from piecewise parabolic fits. *Agron. J.* **64,** 538–542.

Eaton, F. M., and Belden, G. O. (1929). Leaf temperatures of cotton and their relation to transpiration, varietal differences, and yields. *U.S., Dep. Agric., Tech. Bull.* **91.**

Ehlers, J. H. (1915). The temperature of leaves of pinus in winter. *Am. J. Bot.* **2,** 32–70.

Ehrler, W. L. (1973). Cotton leaf temperatures as related to soil water depletion and meteorlogical factors. *Agron. J.* **65,** 404–409.

Ehrler, W. L., Idso, S. B., Jackson, R. D., and Reginato, R. J. (1978a). Wheat canopy temperature: Relation to plant water potential. *Agron. J.* **70**, 251–256.

Ehrler, W. L., Idso, S. B., Jackson, R. D., and Reginato, R. J. (1978b). Diurnal changes in plant water potential and canopy temperature of wheat as affected by drought. *Agron. J.* **70**, 999–1004.

Fuchs, M., and Tanner, C. B. (1966). Infrared thermometry of vegetation. *Agron. J.* **58**, 597–601.

Fuchs, M., Kanemasu, E. T., Kerr, J. P., and Tanner, C. B. (1967). Effect of viewing angle on canopy temperature measurements with infrared thermometers. *Agron. J.* **59**, 494–496.

Gardner, B. R., Blad, B. L., and Watts, D. G. (1981a). Plant and air temperatures in differentially irrigated corn. *Agric. Meteorol.* **25**, 207–217.

Gardner, B. R., Blad, B. L., Garrity, D. P., and Watts, D. G. (1981b). Relationships between crop temperature, grain yield, evaptranspiration and phenological development in two hybrids of moisture stressed sorghum. *Irrig. Sci.* **2**, 213–224.

Gardner, B. R., Blad, B. L., Maurer, R. E., and Watts, D. G. (1981c). Relationship between crop temperature and the physiological and phenological development of differentially irrigated corn. *Agron. J.* **73**, 743–747.

Gates, D. M. (1964a). Leaf temperature and transpiration. *Agron. J.* **56**, 273–277.

Gates, D. M. (1964b). Characteristics of soil and vegetated surfaces to reflected and emitted radiation. *Proc. Int. Symp. Remote Sens. Environ., 3rd, 1964*, pp. 573–600.

Gates, D. M. (1968). Sensing biological environments with a portable radiation thermometer. *Appl. Opt.* **7**, 1803–1809.

Gear, R. D., Dransfield, A. S., and Campbell, M.D. (1977). Irrigation scheduling with neutron probe. *J. Irrig. Drain. Div., Am. Soc. Civ. Eng.* **103** (IR3), 291–298.

Geiser, K. M., Slack, D. C., Allred, E. R., and Stange, K. W. (1982). Irrigation scheduling using crop canopy-air temperature difference. *Trans. ASAE* (in press).

Guinn, G., Mauney, J. R., and Fry, K. E. (1981). Irrigation scheduling and plant population effects on growth, bloom rates, boll abscission, and yield of cotton. *Agron. J.* **73**, 529–534.

Hatfield, J. L. (1979). Canopy temperatures: The usefulness and reliability of remote measurements. *Agron. J.* **71**, 889–892.

Heermann, D. F., and Duke, H. R. (1978). Evaluation of crop water stress under limited irrigation. *Pap.—Am. Soc. Agric. Eng.* **78-2556**, 1–12.

Heermann, D. F., Haise, H. R., and Mickelson, R. H. (1976). Scheduling center pivot sprinkler irrigation systems for corn production in eastern Colorado. *Trans. ASAE* **19**, 284–287, 293.

Heilman, J. L., Kanemasu, E. T., Rosenberg, N. J., and Blad, B. L. (1976). Thermal scanner measurement of canopy temperatures to estimate evapotranspiration. *Remote Sens. Environ.* **5**, 137–145.

Heilman, J. L., Heilman, W. E., and Moore, D. G. (1981). Remote sensing of canopy temperature at incomplete cover. *Agron. J.* **73**, 403–406.

Hiler, E. A., and Clark, R.N. (1971). Stress day index to characterize effects of water stress on crop yields. *Trans. ASAE* **14**, 757–761.

Hiler, E. A., Howell, T. A., Lewis, R. B., and Boos, R. P. (1974). Irrigation timing by the stress day index method. *Trans. ASAE* **17**, 393–398.

Howell, T. A., Jordan, W. R., and Hiler, E. A. (1979). Evaporative demand as a plant stress. *In* "Modification of the Aerial Environment of Plants" (B. J. Barfield and J. F. Gerber, eds.), Monogr. No. 2, pp. 97–113. Am. Soc. Agric. Eng., St. Joseph, Missouri.

Hsiao, T. C. (1973). Plant response to water stress. *Annu. Rev. Plant Physiol.* **24**, 519–570.

Idso, S. B., and Baker, D. G. (1967). Relative importance of reradiation, convection, and transpiration in heat transfer from plants. *Plant Physiol.* **42**, 631–640.

Idso, S. B., and Ehrler, W. L. (1976). Estimating soil moisture in the root zone of crops: A technique adaptable to remote sensing. *Geophys. Res. Lett.* **3**, 23–25.

Idso, S. B., and Jackson, R. D. (1968). Significance of fluctuations in sky radiant emittance for infrared thermometry. *Agron. J.* **60,** 388–392.

Idso, S. B., Jackson, R. D., Ehrler, W. L., and Mitchell, S. T. (1969). A method for determination of infrared emittance of leaves. *Ecology* **50,** 899–902.

Idso, S. B., Jackson, R. D., and Reginato, R. J. (1977). Remote sensing of crop yields. *Science* **196,** 19–25.

Idso, S. B., Reginato, R. J., Jackson, R. D., and Pinter, P. J., Jr. (1981a). Foliage and air temperatures: Evidence for a dynamic "equivalence point." *Agric. Meteorol.* **24,** 223–226.

Idso, S. B., Reginato, R. J., Reicosky, D. C., and Hatfield, J. L. (1981b). Determining soil-induced plant water potential depressions in alfalfa by means of infrared thermometry. *Agron. J.* **73,** 826–830.

Idso, S. B., Jackson, R. D., Pinter, P. J., Jr., Reginato, R. J., and Hatfield, J. L. (1981c). Normalizing the stress degree day for environmental variability. *Agric. Meteorol.* **24,** 45–55.

Jackson, R. D. (1981). Soil moisture inferences from thermal infrared measurements of vegetation temperatures. *Dig., Int. Geosci. Remote Sens. Symp., 1981* Vol. I, pp. 364–374.

Jackson, R. D., and Idso, S. B. (1969). Ambient temperature effects in infrared thermometry. *Agron. J.* **61,** 324–325.

Jackson, R. D., and Pinter, P. J., Jr. (1981). Detection of water stress in wheat by measurement of reflected solar and emitted thermal IR radiation. *Int. Colloq. Spectral Signatures Objects Remote Sens., 1981,* pp. 399–406.

Jackson, R. D., Reginato, R. J., and Idso, S. B. (1977). Wheat canopy temperature: A practical tool for evaluating water requirements. *Water Resour. Res.* **13,** 651–656.

Jackson, R. D., Reginato, R. J., Pinter, P. J., Jr., and Idso, S. B. (1979). Plant canopy information extraction from composite scene reflectance of row crops. *Appl. Opt.* **18,** 3775–3782.

Jackson, R. D., Pinter, P. J., Jr., Reginato, R. J., and Idso, S. B. (1980). Hand-held radiometry. *Agric. Rev. Man., West. Ser. (U.S. Dep. Agric., Sci. Educ. Adm.)* **ARM-W-19,** 1–66.

Jackson, R. D., Idso, S. B., Reginato, R. J., and Pinter, P. J., Jr. (1981). Canopy temperature as a crop water stress indicator. *Water Resour. Res.* **17,** 1133–1138.

Jensen, M. E., ed. (1974). "Consumptive Use of Water and Irrigation Water Requirements," Irrig. Drain. Div., Am. Soc. Civ. Eng., New York.

Jensen, M. E., and Haise, H. R. (1963). Estimating evapotranspiration from solar radiation. *J. Irrig. Drain. Div., Am. Soc. Civ. Eng.* **89,** 15–41.

Jensen, M. E., and Wright, J. L. (1978). The role of evapotranspiration models in irrigation scheduling. *Trans. ASAE* **21,** 82–87.

Kanemasu, E. T., ed. (1975). "Measurement of Stomatal Aperature and Diffusive Resistance," Bull. No. 809. Washington State University, Pullman. pp. 39.

Kanemasu, E. T., Rasmussen, V. P., and Bagley, J. (1978). Estimating water requirements for corn with a pocket calculator. *Kans., Agric. Exp. Stn., Bull.* **615,** 1–24.

Kincaid, D. C., and Heermann, D. F. (1974). Scheduling irrigations using a programmable calculator. *U.S., Agric. Res. Serv. [Rep.]* **ARS-NC-12,** 1–55.

Linacre, E. T. (1964). A note on a feature of leaf and air temperatures. *Agric. Meteorol.* **1,** 66–72.

Linacre, E. T. (1967). Further notes on a feature of leaf and air temperature. *Arch. Meteorol., Geophys. Bioklimatol., Ser. B* **15,** 422–426.

Longnecker, D. E., and Lyerly, P. J. (1969). Moisture content of cotton leaves and petioles as related to environmental moisture stress. *Agron. J.* **61,** 687–690.

Lorenz, D. (1968). Temperature measurements of natural surfaces using infrared radiometers. *Appl. Opt.* **7,** 1705–1710.

McGinnies, W. J., and Aronson, R. C. W. (1971). Effects of environment on an infrared field thermometer. *Agron. J.* **63,** 813–814.

Millard, J. P., Jackson, R. D., Goettelman, R. C., Reginato, R. J., and Idso, S. B. (1978). Crop

water-stress assessment using an airborne thermal scanner. *Photogramm. Eng. Remote Sens.* **44**, 77–85.

Miller, E. C., and Saunders, A. R. (1923). Some observations on the temperature of the leaves of crop plants. *J. Agric. Res.* **26**, 15–43.

Monteith, J. L. (1973). "Principles of Environmental Physics." Arnold, London.

Monteith, J. L., and Szeicz, G. (1962). Radiative temperature in the heat balance of natural surfaces. *Q. J. R. Meteorol. Soc.* **88**, 496–507.

Myers, V. I., and Allen, W. A. (1968). Electrooptical remote sensing methods as nondestructive testing and measuring techniques in agriculture. *Appl. Opt.* **7**, 1819–1838.

Myers, V. I., and Heilman, M. D. (1969). Thermal infrared for soil temperature studies. *Photogramm. Eng.* **35**, 1024–1032.

Nakayama, F. S., and Reginato, R. J. (1982). Simplifying neutron moisture meter calibration. *Soil Sci.* (in press).

Okuyama, T. (1975). Measurements of active surface temperature of rice plant grown in a small model of the paddy field using an infrared thermometer. *J. Agric. Met.* **30**, 191–194 (in Japanese, translated by M. Nakayama).

Park, A. B., Colwell, R. N., and Myers, V. I. (1968). Resource survey by satellite: Science fiction coming true. *USDA Yearb. Agric.* pp. 13–19.

Penman, H. L. (1948). Natural evaporation from open water, bare soil and grass. *Proc. Soc. London, Ser. A* **193**, 120–145.

Perrier, A. (1971). Leaf temperature measurement. *In* "Plant Photosynthetic Production Manual and Methods" (Z. Sestak, J. Gatsky, and P. G. Jarvis, eds.), pp. 632–671. Junk, The Hague.

Pinter, P. J., Jr. (1982). Remote sensing of microclimatic stress. *In* "Biometerology in integrated Pest Management" (J. L. Hatfield and I. J. Thompson, eds.), pp. 101–146. Academic Press, New York.

Rameaux (1843). Des températures végétales. *Ann. Sci. Nat., Bot. Biol. Veg.* **19**[2], 10.

Ritchie, J. T. (1981). Soil water availability. *Plant and Soil* **58**, 327–338.

Russell, G. (1980). Crop evaporation, surface resistance and soil water status. *Agric. Meteorol.* **21**, 213–266.

Sandhu, B. S., and Horton, M. L. (1978). Temperature response of oats to water stress in the field. *Agric. Meteorol.* **19**, 329–336.

Scholander, P. F., Hammel, H. T., Bradstreet, E. D., and Hemmingsen, E. A. (1965). Sap pressure in vascular plants. *Science* **148**, 339–346.

Seguin, B., and Petit, V. (1980). "Utilisation de la thermographie infrarouge pour l'estimation de l'évaporation. Analyse critique des résultats des mésures sur le site de la Crau," TELLUS Newsl. No 16. Comm. Eur. Commun.

Selby, J. E. A., Kneizys, F. X., Chetwynd, J. H., Jr., and McClatchey, R. A. (1978). "Atmospheric Transmittance/Radiance: Computer Code LOWTRAN IV," Air Force Geophys. Lab. Rep. No. AFGL-TR-78-0053. Hanscom AFB, Massachusetts.

Stegman, E. C., Schiele, L. H., and Bauer, A. (1976). Plant water stress criteria for irrigation scheduling. *Trans. ASAE* **19**, 850–855.

Stevenson, K. R., and Shaw, R. H. (1971). Effects of leaf orientation on leaf resistance to water vapor diffusion in soybean (Glycine max L. Merr) leaves. *Agron. J.* **63**, 327–329.

Stone, L. R., and Horton, M. L. (1974). Estimating evapotranspiration using canopy temperatures: Field evaluation. *Agron. J.* **66**, 540–545.

Sumayao, C. R., Kanemasu, E. T., and Brakke, T. W. (1980). Using leaf temperature to assess evapotranspiration and advection. *Agric. Meteorol.* **22**, 153–166.

Sutherland, R. A., and Bartholic, J. F. (1977). Significance of vegetation in interpreting thermal radiation from a terrestrial surface. *J. Appl. Meteorol.* **16**, 759–763.

Sutherland, R. A., Bartholic, J. F., and Gerber, J. F. (1979). Emissivity correction for interpreting thermal radiation from a terrestrial surface. *J. Appl. Meteorol.* **18,** 1165-1171.

Szeicz, G., and Long, I. F. (1969). Surface resistance of crop canopies. *Water Resour. Res.* **5,** 622-633.

Szeicz, G., Enrodi, G., and Tajchman, S. (1969). Aerodynamic and surface factors in evaporation. *Water Resour. Res.* **5,** 380-394.

Tanner, C. B. (1963). Plant temperatures. *Agron. J.* **55,** 210-211.

Thom, A. S., and Oliver, H. R. (1977). On Penman's equation for estimating regional evaporation. *Q. J. Roy. Meteorol. Soc.* **103,** 345-357.

Van Bavel, C. H. M. (1967). Changes in canopy resistance to water loss from alfalfa induced by soil water depletion. *Agric. Meteorol.* **4,** 165-176.

Van Bavel, C. H. M., and Ehrler, W. L. (1968). Water loss from a sorghum field and stomatal control. *Agron. J.* **60,** 84-86.

Van Bavel, C. H. M., Nixon, P. R., and Hauser, V. L. (1963). Soil moisture measurement with the neutron method. **USDA ARS-41-70,** 1-39.

Waggoner, P. E., and Shaw, R. H. (1952). Temperature of potato and tomato leaves. *Plant Physiol.* **27,** 710-724.

Walker, G. K., and Hatfield, J. L. (1979). Test of the stress-degree-day concept using multiple planting dates of red kidney beans. *Agron. J.* **71,** 967-971.

Wallace, R. H., and Clum, H. H. (1938). Leaf temperatures. *Am. J. Bot.* **25,** 83-97.

Watson, A. N. (1934). Further studies on the relation between thermal emissivity and plant temperatures. *Am. J. Bot.* **21,** 605-609.

Wiegand, C. L., and Namken, L. N. (1966). Influences of plant moisture stress, solar radiation, and air temperature on cotton leaf temperature. *Agron. J.* **58,** 552-556.

Wiegand, C. L., Heilman, M. D., and Gerbermann, A. H. (1968). Detailed plant and soil thermal regime in agronomy. *Proc. Int. Symp. Remote Sens. Environment, 5th, 1968,* pp. 325-342.

Wolpert, A. (1962). Heat transfer analysis of factors affecting plant leaf temperature. Significance of leaf hair. *Plant Physiol.* **37,** 113-120.

Wright, J. L., and Jensen, M. E. (1978). Development and evaluation of evapotranspiration models for irrigation scheduling. *Trans. ASAE* **21,** 88-96.